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MATERIALS HANDLING FOR TUNNELING

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16. Abstract

At the tunnel face advance rates anticipated for the future, material handling could become the critical factor in the tunneling project. All functional elements of the tunneling process require materials to be moved by the materials handling system. The characteristics, quantities, and flow of muck, ground support materials, materials for transport system extension, personnel, and other materials and equipment which must be transported between the surface and the work zones are defined. Candidate transport modes to meet the requirements of the future are classified as continuous flow systems or unitized transport systems.

Conveyors, hydraulic pipelines, and pneumatic pipelines are selected as representative of continuous flow systems. Conventional dual rail systems with locomotive drive, side-wheel drive and cable drive, siderail systems, monorail systems, hoists, and truck systems are selected for evaluation in the unitized category. These ten transport modes are described, discussed, and analyzed through computerized mathematical models representing the cost/performance relationship for each system. Integrated systems including all elements of the total materials transport system throughout its total life cycle are conceived and analyzed. Based on the results of these evaluations and analyses, areas are identified for beneficial allocation of research and development resources to advance the state of the art of materials handling for tunneling.

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PREFACE

The results of a systems analysis of materials handling for tunneling are described in this report. The study was sponsored by the Office of High Speed Ground Transportation and the Urban Mass Transportation Administration of the U. S. Department of Transportation under Contract No. DOT-FR-00002. The project was under the technical direction of William N. Lucke of the Office of High Speed Ground Transportation.

Substantially all of the work under this contract was performed by Holmes & Narver, Inc., Los Angeles, as prime contractor and Resource Management Corporation, Santa Monica, as subcontractor for cost/performance analysis. R. B. Wyman, Tunneling Consultant, University of Nevada; H. F. Haller, Mining Engineer, and H. F. Perla, Manager of Projects, both of Holmes & Narver, reviewed report drafts and made valuable suggestions.

Contributions to the effort were made by Holmes & Narver (H&N) and Resource Management (RMC) personnel as follows:

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Loren H. Riechers (RMC)	Programming

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PART 1: SYSTEM DESCRIPTIONS

INTRODUCTION

One of the basic problems confronting the attainment of intercity high speed ground transportation systems, particularly through urban areas, and fulfillment of the needs for urban mass transportation systems is the high cost and time required for tunneling.

Considerable effort is underway to advance the technology of excavation which can result in significant increases in the rate of advance of the tunnel face. As the rate of excavation increases, the rate of construction of the earth support system in the working area must be increased; and as the rate of face advance and/or diameter of the tunnel increases, the quantity of muck which must be removed from the tunnel increases. If the advancement of the technology of these operations does not keep pace with advances in excavation, either muck removal or earth support construction can become the limiting constraint on the forward movement of the tunnel face. One of the limiting factors in the rate of construction of the earth support system is the transport of construction materials and supplies to the working area.

It is, therefore, imperative that a systematic effort be directed to the improvement of methods of materials handling for tunneling operations if continuing improvement in the rate of tunneling is to be achieved. This report represents the results of the first step in this systematic approach. It provides

- An overview of the tunneling process viewed as an integrated system.

- Identification of the quantities and characteristics of all materials which must be transported by the material handling system.

- Identification of other functional requirements imposed on the material handling system.

- Identification of candidate transport modes to meet the materials handling requirements, with evaluation of the strengths and weaknesses of each mode.

- Computerized parametric models to generate cost/performance data for transport modes and integrated material handling systems, suitable for continuing evaluation of the advancing technology of tunnel materials handling.

- A generalized evaluation of material transport modes in a tunnel environment.

- Identification of areas related to each transport mode for beneficial application of research and development resources.

This study was conducted to identify the material handling requirements of the future, the material handling concepts which offer the best potential for meeting these requirements, and the developments which must take place to achieve practical systems. The study emphasizes the comparative evaluation of existing and projected long-haul transport systems for haulage of those materials which must be continuously provided to or removed from the near-face zone to support rates of excavation far beyond those achieved with present technology. The tunnel configurations considered are those anticipated for tunnel projects of the future to construct very long tunnels for deep underground transportation systems.

The report is divided into four major parts. Part 1, Systems Descriptions, reviews a typical tunneling project in Chapter 1 and presents the tunneling process as a total, highly interrelated system. Chapter 2 discusses the interrelationship of the various transport modes which are discussed in greater detail in Chapters 3 and 4 and combined into typical integrated system concepts in Chapter 5.

Part 2, Logistic Requirements, discusses the flow characteristics of in-bound and out-bound materials and summarizes the quantities of the major materials in Chapter 6. Chapter 7 discusses the characteristics of muck and a possible approach to the development of a muck characterization index. Ground support materials and materials for extension of all systems are described in detail in Chapters 8 and 9. Personnel and other intermittently required materials and equipment are described in Chapters 10 and 11.

Part 3, Systems Analysis, includes in Chapter 12 an outline of the approach used for the analysis, a material handling system life-cycle scenario for a typical tunneling project, and definition of the life-cycle cost elements. Appendix 3B includes discussion of the development of cost/performance models and detailed analysis for the various transport modes.

The results of these analyses are compared in Chapter 13. The integrated system model including all life-cycle cost elements is described in Chapter 14 and the cost estimating relationships used in the model are summarized in Appendix 3A. A comparative evaluation of selected integrated systems is presented in Chapter 15.

Part 4 discusses research and development needs identified on the basis of the background material developed in Parts 1 and 2, and the results of the analyses in Part 3.

SUMMARY

PART 1 - SYSTEM DESCRIPTIONS

Chapter 1 - The Tunnel Project

A large-scale tunneling project is described as a total system consisting of four highly interrelated major functions; excavation, ground support, project support, and materials handling. Current practice related to each of these functions is reviewed briefly and the major elements of each function are displayed as a project systems hierarchy. Factors affecting the materials handling problem, due to the geometry of the tunnel complex, are identified and the various material handling situations which may be encountered are discussed.

Chapter 2 - Material Handling Systems

The functional requirements of the material handling system and the types of materials to be transported are summarized. The material handling system of concern is defined as the hardware system required to transport all substance (not carried by independent service lines) that move between the surface support area and the underground work zones. Major emphasis is given to the long-haul transport of those materials which must flow continuously between the end points of the system. Candidate transport modes are grouped by functional type into a hierarchy of transport systems, the characteristics of system types are discussed, and a comparison is made between continuous flow systems and unitized systems. Auxiliary equipment such as loaders, transfer equipment unloaders, and processors is discussed briefly.

Chapter 3 - Continuous Flow Systems

Continuous flow systems include conveyors and hydraulic and pneumatic pipelines. The characteristics, state of development, strengths, and weaknesses of each of these transport modes are discussed in detail.

Chapter 4 - Unitized Transport Systems

Unitized systems include locomotive driven, side-wheel driven, and cable driven conventional rail systems, siderail systems, monorail systems, hoists, and truck systems. The general characteristics of these systems, the characteristics, state of development, strengths, and weaknesses of each of these transport modes are discussed in detail.

Chapter 5 - Integrated Systems

Concepts are developed for typical integrated systems to meet the requirements for transport of inbound and outbound materials in horizontal, inclined, and vertical attitudes. Sketches are developed to illustrate relationships and space problems in the shaft station and near-face zone.

PART 2 - LOGISTIC REQUIREMENTS

Chapter 6 - Flow and Quantity of Materials

The flow characteristics of inbound and outbound materials and the impact on material transport systems are discussed. Speed of material flow, constraints on flow due to environmental factors, attitudes of movement, requirement for intermode transfer, congestion, queuing, transport loops, and variations in material flow are considered. A summary of material characteristics and tabular and graphical summaries of the major material quantities are included.

Chapter 7 - Muck Characteristics

Underground conditions anticipated for deep transportation systems are typified by the geologic and engineering conditions found in the Northeast Corridor. Various types of muck which might be encountered with various excavation methods are identified and interrelated to engineering properties. Muck relationships to the rock quality designation (RQD), hardness, abrasiveness, drillability, and compressive strength are summarized. A possible approach to development of a muck characterization index called the muckability designation number (MDN) is presented.

Chapter 8 - Ground Support Materials

The four basis methods (rock bolts, shotcrete, rib sets, and liner segments) of installed ground support are discussed and the characteristics and quantities of materials used in each method are identified in detail.

Chapter 9 - Materials for Systems Extension

Systems which must be extended in pace with the advancing tunnel face are the material transport system and utility service lines such as ventilation, compressed air, service water, ground water removal, and electric power and light. The quantity of material required per foot of tunnel and the material flow rate for extension of these systems for various advance rates and tunnel diameters are summarized.

Chapter 10 - Personnel

Operation and maintenance crews which must be transported within the tunnel complex impose a requirement on the material handling system. Crew sizes are estimated for alternate methods of excavation, ground support, material handling, and project support for various advance rates and tunnel diameters.

Chapter 11 - Other Materials and Equipment

In addition to muck, ground support materials, materials for systems extension, and personnel, the material transport system must carry other materials and equipment required for excavation, for installation of structural support for apparatus to be installed at a later date, for installation of ground support materials, for ground stabilization, and for other project support functions. These materials, and others not normally carried by the material transport system but moved through the tunnel space, are discussed.

PART 3 - SYSTEMS ANALYSIS

Chapter 12 - Systems Analysis Approach

A "life cycle scenario" for a material handling system used in a typical tunneling situation traces the material handling system from development and acquisition (birth) through final salvage or discard (death) including all life cycle cost elements. The four phases of the analysis method are outlined and the various transport modes and integrated systems analyzed are indicated.

Chapter 13 - Comparison of Transport Modes

The analysis of transport modes discussed in detail in Appendix 3B produced two sets of cost/performance data expressed in consistent terms and designated specific cost. In addition, the transport mode analysis identified the elements of equipment cost and operating cost which make major contributions to the overall cost of the transport system. These data provide a consistent data base in simple parametric form for comparison of transport modes and for input data to the analysis of integrated or total system concepts for material transport in particular tunneling situations.

Chapter 14 - Integrated Systems Model

The integrated systems model is designed to accept cost data generated by the system cost models for the various modes of transport selected for horizontal and vertical transport and combine these cost data with cost data for transport system extension, loading, and intermode transfer at the shaft station. "Integrated systems" are "constructed" out of transport, extension, loading, and transfer systems by selecting a logical combination of these functional systems. Cost estimating relationships are developed and summarized in Appendix 3A for each material handling functional system. Integrated system costs are obtained by summing appropriate functional system costs for the advance rate, tunnel diameter, configuration, construction strategy, and other factors which define the case being studied.

Chapter 15 - Evaluation of Integrated Systems

The possible number of integrated systems and project situations is very large. A limited number of integrated systems were evaluated, with many of the input parameters held constant, over the following ranges: 300 to 1,500 feet/day tunnel advance rate; 10 to 40 feet tunnel diameter; 500 to 3,500 feet tunnel depth. Results are expressed as total materials handling cost in dollars per linear foot of tunnel produced. The systems models can be used to generate cost data for any other systems and situations desired.

PART 4 - RESEARCH AND DEVELOPMENT

Chapter 16 - Research and Development Needs

Based on the comparison of cost/performance for transport modes, evaluation of integrated systems, and operating characteristics and limitations of the candidate transport systems, specific problem areas for beneficial application of research and development resources are identified for each transport method appearing worthy of further development.

CHAPTER 1

THE TUNNEL PROJECT

Large underground excavation projects usually consist of a complex of chambers and interconnected tunnels as seen in:

- Subway systems.
- Underground pumped storage power plants and mining operations.
- Long runs of relatively straight tunnel for transportation of water through mountains or for gaining access to deeply buried ore bodies.

The magnitude of tunnel and underground excavation projects of the future can be visualized by comparison with some of the larger projects of the past. The Northfield Mountain underground pumped storage power project required approximately 500,000 cubic yards of excavation. Long tunnels (over 10 miles) for water transportation or access to ore bodies might require excavations of the order of 1.5 to 2 million cubic yards. Large subway systems and mining operations might involve in the range of 50 million cubic yards of excavation over a period of the many years required for full development of the project.

Some proposals which have been made for a possible solution to the problem of high-speed ground transportation in corridors of heavy population and industrial congestion involve the use of underground, intercity transportation systems. Candidate corridors for future application of this solution vary in length from less than 40 miles (Washington/Baltimore) to over 400 miles (Los Angeles/San Francisco, Washington/Boston). At the upper extreme, these projects would require between 60 and 120 million cubic yards of excavation in a period of a few years. To complete only one project of this magnitude in 3 years with today's best sustained tunnel driving rates would require machines boring simultaneously under ideal conditions at 25 to 50 headings. The large capital investment required for excavation and construction equipment provides strong incentive to increase the heading advance rate. High advance rates also favor lower operating costs due to the decrease in total hours of operation, so it is evident that very substantial savings will be realized as the advance rate is increased. As the excavation rate increases, the rate of installation of ground support must keep pace; and the rate of removal of muck and supply of ground support materials must increase to meet the demands of the excavation and construction operations.

In order to evaluate the suitability of alternate methods of material handling and to identify the severity of material handling problems as these rates increase, maximum rates of advance have been selected for this study well beyond those that appear to be reasonable extrapolations of today's capability. An upper limit for the sustained average rate of face advance has been selected at 750 feet per 24-hour day. To achieve this average, peak rates up to 1,500 feet per day are assumed. The material handling system must be capable of removing muck and delivering construction materials at the peak rate, since at these rates of advance space is not available for more than a few minutes of surge-storage capacity.

The study is directed to the technology required for tunnel projects of the future to construct very long tunnels deep underground which will be larger and more complex than any tunneling projects attempted to date.

THE TUNNELING PROCESS

A hypothetical, large-scale tunneling project is shown schematically in Figure 1-1. It consists of a number of interrelated activities taking place at various locations in the tunnel and on the surface. The major activities are:

- Excavation, which consists of breaking or fragmentation and removal of in-situ rock or soil.
- Ground support installation and maintenance to assure the safety of the tunnel.
- Transport of muck or spoil from the excavation area to a disposal site on the surface.
- Transport of construction materials from the surface to the point of installation or usage.
- Transport on a shift cycle of personnel to and from the work sites within the tunnel complex.
- Provision of an environment adequate for equipment and personnel to perform their functions.
- Maintenance of operating equipment.
- Aboveground operations required to support underground activities.

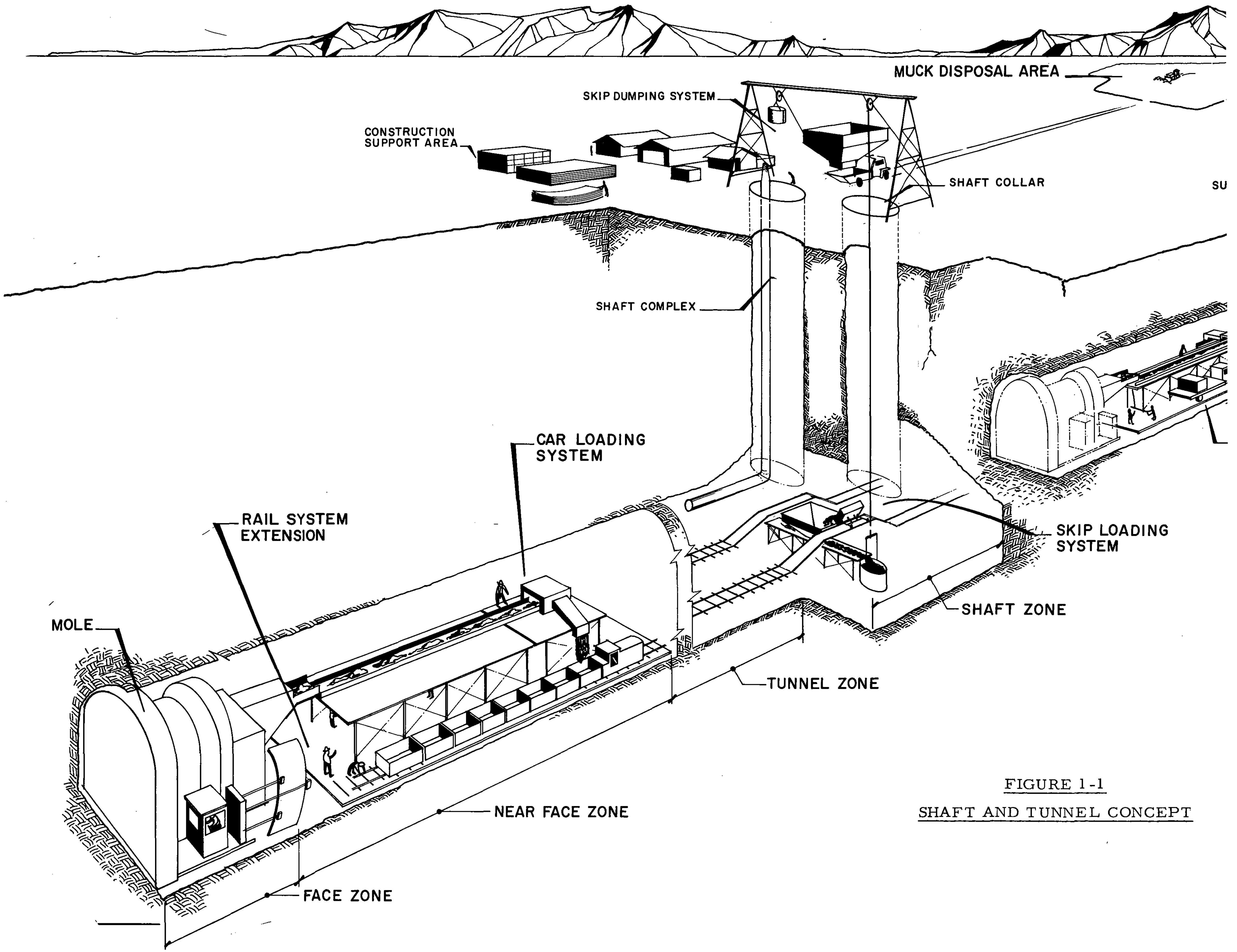

FIGURE 1-1

SHAFT AND TUNNEL CONCEPT

Although sharp distinction cannot be made between some adjacent work areas, several zones can be identified based on the function performed or the location in the tunnel complex. These are:

- The excavation or face zone.
- The construction or near-face zone.
- The horizontal transport or tunnel zone.
- The transfer zone or shaft station.
- The vertical transport zone or shaft.
- The inclined transport zone (inclined shaft or inclined tunnel).
- The construction support area.
- The dump site (muck disposal area).

Fragmentation of rock and removal from its in-situ position is performed in the face zone which also includes gathering the muck or displaced rock from the floor of the tunnel. All, or at least the front, of the excavating machine or shield operates in this zone.

Immediately behind the excavation zone the broken rock or muck is loaded onto a transport system for removal from the tunnel, and ground support materials are installed. In addition, the material transport system must be extended at the same rate as the advance of the excavation face. This zone, which extends from the face zone for several hundred feet, is the construction area or near-face zone.

Muck is removed, and construction materials, supplies, and personnel are transported to the construction area through the horizontal transport zone which provides the only means of access to the face and near-face zones. The transport distance between the near-face zone and shaft station, or portal in the case of portal access tunnels, increases as the face advances away from the shaft or portal. In this study, the tunnel is considered to be nearly horizontal with grades less than 3 percent. Tunnel segments with grades greater than 3 percent are called inclines.

Large-diameter single shafts or clusters of smaller shafts are sunk to provide access and ventilation for the tunnel both during construction and for use of the tunnel when completed. They are usually vertical but can be inclined. Thus, an inclined segment of the tunnel complex may serve as a shaft or part of the tunnel depending on the use. If the incline is to serve the primary function of the tunnel, it is an inclined tunnel; if it is to provide service support to the tunnel, it is an inclined shaft. For deep tunnels, shafts or inclined tunnel segments are the only means of access to the tunnel, and all materials must pass through one of these access-ways. The surface opening of a shaft is the collar; for a tunnel, it is a portal.

When different modes are used for transport through the tunnel and lift through the shaft, a transfer of material between modes occurs at the juncture of the tunnel and shaft. This area, called the shaft station, is an enlarged section of the tunnel and may extend into the tunnel zone to provide the required work area. Materials are sometimes stored temporarily in this area, and intermittently used equipment may be repaired or stored here between periods of use. Combinations of material transport modes may require processing of materials in this area. For example, rail transport of muck from the construction area to the shaft station followed by hydraulic lift to the surface might require particle size reduction at the shaft station prior to loading the muck into the hydraulic system.

Life support and other project support activities are required in all areas of the tunnel complex. This includes provision of suitable ventilation, temperature, humidity, and dust control; provision of light, potable water and sanitary facilities; maintenance of all equipment; operational supervision and safety of personnel; tunnel alignment; inspection, testing, and assurance of the integrity of the ground support system; and emergency operations. In addition, waste materials from various operations and water that runs into the tunnel complex must be removed as they accumulate.

All activities performed within the tunnel complex are severely affected by the space limitation and single-route access provided by the tunnel configuration. Another aspect of the tunnel process which contributes to the complexity of operations is the requirement that all activities move forward and keep pace with the face advance. This requires constant repositioning of equipment and extension of supply lines and material transport systems. The materials required to make these extensions add to the load imposed on the material handling system.

The dependence of each of the underground acitivities on all other activities is so great that lack of synchronization in performance will quickly reduce the rate of advance to the limiting value provided by the restricting component of the system. For example, a reduction in the rate of muck removal will soon result in a muck-bound condition slowing the production rate of the excavation equipment. If the installation of ground support materials falls too far behind the excavation face due to difficulty of installation or shortage of materials, the resulting unsafe condition would require a reduction in the rate of advance.

These constraints impose a strong requirement for careful planning and coordination of activities if sustained high rates of advance are to be achieved. Application of mechanization and automatic control of many activities may be justified.

A construction support area is normally located in the vicinity of the shaft collar or tunnel portal. Welding, pipe, carpentry, and machine shops are located here to provide parts for and maintenance of equipment and materials required for tunnel driving operations. Material and equipment storage yards are provided as well as facilities for job supervision. Life support and utility facilities such as blowers, compressors, water pumps, electric generators, and cable drives are also found here. If it is necessary to change the mode of material transport at the collar or portal, transfer mechanisms or facilities are required. This may involve changing the form of the material being handled. For example, if the muck is hydraulically lifted from the tunnel, dewatering might be required before transport to the dump site.

The dump sites for disposal of muck and other waste may be close to the construction support area; or they may be several miles away, depending on the conditions at the collar or portal. Regardless of the mode used for transport of muck to the dump site, access to the construction support area must be provided by a mode of transportation suitable for bringing in the construction materials, supplies, equipment, and personnel. This requires some form of road, rail, or aerial tramway system.

Excavation

Current practice in tunneling utilizes either a cyclic or continuous excavation method depending largely upon the type of material being excavated and the tunnel configuration. The cyclic or conventional method is the oldest and currently provides the most efficient and versatile application of energy. Usually this method consists of a repetitive cycle consisting of drilling, blasting, mucking, and ground support installation operations. In loose or running ground, or where a mixed face is encountered, hand excavation with special techniques such as forepoling, heading and bench, or shield excavation may be required. The rate of muck production by the drill and blast method or hand operations is low compared to future requirements, since advance rates exceeding 50 feet per day are seldom achieved. Although it is not expected that these methods will produce advance rates in excess of 150 feet per day due to the cyclic nature and difficulty of automating the operations, a major breakthrough in drill and blast technology might result in higher advance rates. Simultaneous drilling of multiple blast holes, automatic loading of explosive charges, protection of personnel and equipment by blast shields, and simultaneous loading of muck and installation of ground support have been used or proposed to increase the rate of advance; but, the inherent limitations of the cyclic method remain. Until progress in the technology of excavation provides an excavating machine capable of performing satisfactorily under all ground conditions, a probability exists that cyclic methods of excavation will be required in one or more segments of a tunnel route.

In hard rock, conventional methods produce muck which is usually blocky or slabby; in soft ground, the muck tends to be muddy or pebbly cohesive. Rail cars or rubber-tired vehicles are most often used to transport the muck away from the excavation zone since the demand on the transport system is cyclic.

Continuous or semicontinuous excavation is performed by mechanical excavators. The semicontinuous machine employs a claw-like device for digging material from the tunnel face. It is suitable for relatively soft consolidated material or a matrix of clay or shale with embedded fragmented rock. This machine mechanizes excavation under conditions previously requiring hand excavation. The nonhomogeneous nature of the ground for which this machine is suited and the method of attack on the face make the development of a true continuous operation difficult.

The rotary head machines or "moles" offer promise of sustained continuous excavation under suitable ground conditions when problems of cutter wear and mechanical breakdown are overcome. Two general types are in use: those employing rotation of the complete head as a unit, and those having several smaller rotating cutter heads mounted on the front of the mole. Only full-circle bores can be produced by rotating the complete head. Tunnel cross sections approximating the standard horseshoe-tunnel or other sectional geometry can be produced by the multicutter head machines. These machines are also more adaptable to work on a nonuniform tunnel face.

A mechanical mole is a massive piece of equipment which braces against the tunnel walls, thrusts a set of cutting edges or bits against the face to fragment the in-situ material, and removes the resulting muck from the face zone by scooping it up from the floor and transporting it by conveyor through the mole to the rear of the machine where it is transferred to a transport system for removal from the tunnel. This fairly recent method resulted in substantial increases in the advance rate over the conventional cyclic method. The maximum sustained average rate achieved is in excess of 200 feet per day. Short duration rates as high as 400 feet per day have been obtained. Because of the downtime required for cutter replacement and maintenance on moles currently used, the operation is not fully continuous. Normal availability is only 20 to 30 percent at the present time.

The mole has usually been employed most successfully in soft to medium rock, and found much more limited application or been unsuitable for use in hard rock (above 25,000 pounds per square inch), mixed face situations, sticky clay material, or running ground. Although these machines have been used successfully on several tunnel projects, they are still in the development stage. Improvements are being made in cutters, power trains, and other components to provide better performance and to reduce the downtime of the equipment. Continuing improvements in the penetration rate, the ability to work in a wider range of ground conditions and rock types, and the equipment reliability are expected to provide continuous or near-continuous excavation in the near future.

Advance rates which have been achieved by moles, and even higher advance rates expected on a sustained basis in the future, impose new demands on material handling systems for muck removal and transport of construction materials. Average rates of material transport in the future will be several times the present peak requirements. As the production of muck and the use of materials approach continuous operations, the need for synchronized continuous flow of materials increases since there is limited space for surge storage.

The muck produced by moles working in soft or medium rock consists of relatively small, uniformly coarse granular, tabular, or foliated particles. These muck characteristics are compatible with a broader range of muck transport modes than the large, less uniform, blocky muck produced by the conventional method of excavation.

Many novel approaches have been proposed to increase the excavation rate. Some of the more promising techniques which are now in the research and development phase include flame jet rock disintegration, hydraulic jet shattering, laser, and plasma jet disintegration. The advance which may be achieved by these methods and the characteristics of the muck produced in realistic tunneling situations have not been determined due to the early stage of development of the methods.

Flame jet rock disintegration does not work well in soft rock. It is more effective in the harder rocks, such as granites and gneisses, which have high percentages of silica and high spallability rates. These rocks, which are very hard, are difficult to excavate by mechanical cutters. United Aircraft Research Laboratories[1] has studied a method of incorporating the flame jet principle into a tunneling machine. The concept of this machine for a 30-foot diameter tunnel is shown in Figure 1-2 which also illustrates the massiveness typical of tunneling machines. In this scheme, a series of circular concentric kerfs or channels are produced in the rock face by the flame jets. The rock between the channels is then

30-FT DESIGN
BLOWING/SUCTION AIR SUPPLY

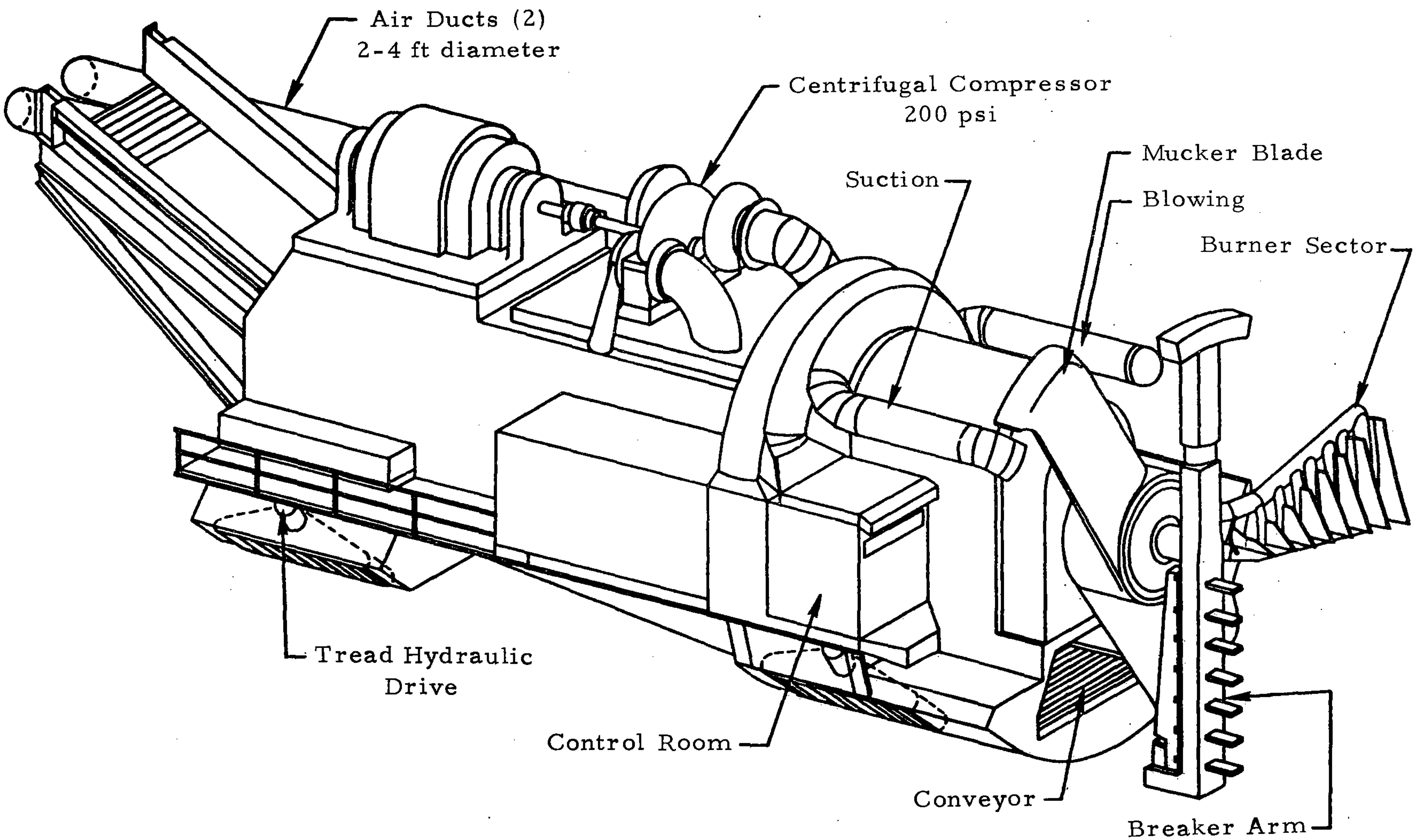

FIGURE 1-2

FLAME-JET TUNNELER
(United Aircraft Research Laboratories)[1]

broken off mechanically by a breaker arm. This approach reduces considerably the requirement for rock spalling by the flame jets since disintegration of the entire face by heat is not required. The tunneling machine would operate behind a heat shield sealing off the entire face area and isolating the heat and gases produced from combustion and rock decomposition. The mucking arrangement on this machine consists of large rotating mucker blades which sweep the muck onto the muck conveyor through one or two openings at the front of the machine. The muck is then transported away on hot material handling grates or pan feeders to be cooled and handled by conventional material handling systems. The handling and cooling of large quantities of hot muck would increase considerably the load on the environmental cooling system.

Under sufficiently high pressure, a jet of water directed at a rock face can shatter the rock. These jets of water can be pulsed intermittently through large nozzles or pumped continuously through small nozzles. Once the minimum threshold pressure required for rock shattering is exceeded by the water jet, the rock breaks. Considerable research is presently underway to determine threshold pressures for various rock types and also to determine the most economical water pressures for rock shattering. Preliminary tests indicate that the rock strength may have less effect on fluid-shattering rates than it has on rock-breaking rates achieved by the mechanical cutters of the conventional mole. Considerable research on hydraulic jet shattering is now underway in the United States and other countries. Current laboratory test penetration rates in various types of rock indicate the possibility of extremely rapid advance rates for future hydraulic jet-shattering systems. Anticipated muck characteristics from fluid shattering are similar to those obtained from mechanical excavators, except that the muck will have a higher moisture content, varying from damp to quite wet depending on the rock type and the shattering technique used. The quantity of water used in the pulsed, high-pressure jet appears, from small-scale tests, to be about 1.5 gallons per cubic yard of in-situ rock.

For the plasma technique of rock disintegration, the specific energy requirements are high. It has, nevertheless, received considerable attention since the energy is applied directly to the rock face and since no losses occur in a transmission train as in the case of mechanical moles. Research in this field to date has been confined entirely to laboratory scale testing. Bouche[2] reports that experience gained in the laboratory indicates that the plasma torch offers a tremendous advantage over conventional chemical flames for many applications. Not only can this new heat source, with its unusually high temperature, perform many tasks previously not possible, but it also produces unit heat output at a lower cost than oxygen requiring fuel when used on an industrial scale.

Westinghouse Research Laboratories[3] has developed a 10-kilowatt electron beam rock cutter. Current work involves investigation of its possible use for tunneling and trenching.

Other approaches being investigated include the use of chemicals or heat applied to the face of the rock to weaken it, making it more susceptible to fracture by mechanical cutters. The rate of chemical reaction tends to limit the maximum advance rate obtainable by this approach. The use of heat to assist mechanical cutters reduces the heat load on the environmental cooling system from that imposed by the use of solely thermal spalling techniques. The approach using heat weakening is currently being investigated by United Aircraft Laboratories.

Other methods of changing the ground characteristics to make it more suitable for application of mechanical moles include freezing the ground with liquid nitrogen or other cryogenic material and forcing chemical or cement grout into small leader holes to consolidate a loose formation. Either of these techniques would require preparation well in advance of the tunneling operation; otherwise, it would severely limit the advance rates due to the time required for ground preparation.

Ground Support

Tunnels most often are driven in materials which are not competent and, therefore, require a ground support system to be installed. The support system may be temporary for sustaining short-term loads or may be installed to sustain longer term loads; but when placed during tunnel driving, it is considered primary lining. When additional lining is placed inside of primary lining or replaces it, that lining is considered secondary and is usually placed after excavation is completed when more working space is available.

When support is required, it should be placed quickly to provide the necessary protection to personnel and equipment. Modern practice[4] indicates that prompt placement of properly designed primary ground support can obtain maximum benefit from the self-supporting capability of the ground, thus reducing the amount of supplementary support required. Therefore, installation of primary support systems takes place as close behind the excavation face as possible, simultaneously with muck removal. This tends to interfere with other activities in the tunneling process.

The design of a muck-removal system must consider the space to be occupied by the support system, the space or clearance to install it, and the space necessary to deliver materials and equipment used in the installation. For a continuous excavation technique, continuous installation of the ground support system at the same rate as the face advance is required.

Therefore, a relatively continuous supply of support materials is required concurrent with excavation and muck removal.

The design of the ground support system, which is dependent on the characteristics of the material being excavated, is selected primarily for its ability to adequately support the ground. However, consideration of economy, rapid installation, permanency, or flexibility is also important. There are five basic methods of ground support which may be used singly or in combination. The first, which is appropriate only for highly competent rock of high-compressive strength, requires no supplemental supporting materials. The load is supported by the natural arch formed in the rock.

For less competent rock, the formation of this arch is aided by the use of rock bolts which penetrate approximately 4 to 10 feet or more into the rock increasing the cohesiveness of the rock and distributing the load. The rock bolts often are supplemented by wire mesh or plates spanning between bolts to prevent the falling of loose rock.

Mass material, such as shotcrete or gunite, may be applied to the surface of the rock to reduce spalling and to act in compression to prevent movement of the rock and loss of cohesiveness. Chemical materials alone, or reinforced with fiber glass, polymerized in place by heat or radiation, have also been suggested and are being developed for this use. Use of these bulk materials may, unless adequately designed equipment and procedures are used, create atmospheric conditions deleterious to material handling systems and other equipment. Spattered material and solvents used as carriers for chemical monomers would need to be carefully controlled.

Where more support is required than provided by rock bolts or mass materials alone, they may be used in combination to obtain the advantage of the load support mechanism of each. Improvements are being made in equipment and technique for the application of shotcrete and in the use of accelerators to achieve very rapid set of the material. Very favorable results have been reported under rather adverse conditions, particularly for the use of dry shotcrete. The new Austrian method(5) of ground support which has been used successfully on several jobs, including very severe ground conditions, during the past 10 years is based on the principle of prompt installation of support including closure of the invert to provide full-ring resistance to ground movement. Careful measurements of ground movement are made to determine when equilibrium has been established so that secondary lining can be installed. The primary support consists of combinations of rock bolts, wire mesh, shotcrete, and steel bar ribs as required by the particular ground condition.

Under more severe load conditions encountered in some squeezing or swelling ground, the usual practice requires the use of rib sets or liner segments. Rib sets are structural steel arches, or full circles, which may be designed to support very heavy loads. The rib set is assembled from two or more components as close behind the working face as is feasible. The components are fabricated outside the tunnel from standard structural steel shapes. Lagging may be used between the rib sets to protect against spalling rock.

Liner segments are structural members of cast iron, steel, or concrete, or a combination of these which can combine the load support capability of rib sets with the full surface protection against falling rock afforded by lagging used with rib sets. In some designs, the initial installation of liner segments also provides the final tunnel surface. In other cases, the final facing is applied later in the construction sequence. For heavy loads, liner segments become massive, weighing several tons each. Heavy-duty equipment is required for handling and installing these components.

Packing is often used in the space between the rock surface and the liner or the ribs and lagging to distribute the rock load uniformly to the structural support system. Yielding packing materials are being investigated as a means of improved load distribution and to accommodate more adequately the changes in distribution which occur with time in squeezing or swelling ground.

Most tunnels constructed for permanent use are lined with concrete to the final design dimensions. Since most designers have not considered this secondary lining to be part of the ground support system, it has been possible to install it after all excavation has been completed, thus avoiding interference with the excavating and ground support operations. However, as more attention is given to reducing the cost of tunnels by improving the design of the ground support systems, there is a strong incentive to install the secondary lining as close behind the excavation as possible. Installing the secondary lining simultaneously with excavation has the obvious disadvantage of reducing the already limited space available for transport of materials and equipment to and from the working zone. This disadvantage might be mitigated by the development of an installation system designed to eliminate or minimize the space conflict. These devices may require space along the sidewalls of the tunnel, thus further restricting flexibility in locating the muck-removal system. The loads imposed on the support system are very difficult and often impossible to predict. They may vary over a wide range in a given segment of tunnel. Therefore, more than one method of support may be required to economically handle the various situations in a tunneling project.

All methods of ground support require transport of materials from the construction support area outside the tunnel complex to the near-face zone where they are installed. Special equipment is required for erection, application, or installation of all ground support systems except the smallest rib segments and pan liners which may be installed manually. Rib set installation with blocking, lagging, and packing requires the largest number of separate operations and is, therefore, the most difficult to mechanize. Progress toward more rapid installation of rock bolts has been made by using multiple drill equipment, but the need for sequential operations cannot be eliminated.

Maintenance of the primary support system from the time of installation until the secondary lining is installed may require onloading or offloading of material at intermediate points along the material transport system, particularly under severe ground conditions where spalling may occur or sections of ground support may need to be replaced.

Of the basic methods, only the mass materials (such as shotcrete) used alone offer the possibility for continuous installation. The materials for this method are transported as loose or packaged bulk materials and are mixed in the near-face zone for application to the rock surface. At the present stage of development, this method produces the largest amount of waste (rebound) material which must be cleaned up and removed from the tunnel complex. Installation of liner segments might approach a continuous process by careful development of procedures and equipment, but it would lack the flexibility to adapt to the variation in load requirement that can be obtained by application of various thicknesses of shotcrete. There is some doubt that shotcrete, even in combination with rock bolts and mesh, will be adequate under heavy squeezing ground or other unusual situations. Ribs or liner segments may always be needed in these cases.

Project Support

Project support includes provision of an adequate environment for personnel and equipment to perform their required functions which are maintenance of all equipment and other miscellaneous support activities such as:

- Supervision of personnel
- Assurance of personnel safety
- Inspection by officials
- Emergency operations
- Tunnel alignment

- Testing (e.g., measurement of ground movement)
- Inspection and assurance of integrity of the installed systems (e.g., ground support, roadbed)
- Removal of waste materials
- Removal of groundwater running into the tunnel

The provision of an adequate working environment and other life support requirements includes:

- An adequate supply of fresh air and removal of noxious gases
- Temperature and humidity control
- Dust control
- Light of proper intensity in work areas and lower levels throughout the tunnel complex
- Comfort items such as potable water and toilet facilities
- Extension of life support systems.

Fresh air ventilation must be provided throughout those segments of the tunnel complex where work is being performed, including the tunnel and shafts where transport and maintenance operations occur. Dust control is an important consideration in the design and operation of the ventilation system. The severity of this problem is affected by the ground condition and methods of excavation, ground support, and muck transport selected. The most common method of dust control is to spray the dust source with water.

Temperature and humidity control is vital to sustained effective performance of personnel. In long tunnels deep underground where rock temperatures may exceed $100^{\circ}F$, it becomes impractical to provide the desired temperature and humidity by increasing the fresh air supply. Refrigeration is required, which means providing a supply of chilled water to carry the heat to a heat sink located outside the tunnel complex. In severe situations, mechanical refrigeration units may be required in the work zones. Any of the proposed thermal methods of rock breaking or weakening will increase the problem of heat removal.

Ventilation air ducts, water circulation pipes, cooling coils, and refrigeration units (if required) must be extended or moved ahead at the same rate as the face advance rate. This requires transport of ducting, pipe, fittings, and support brackets from the construction support area on the surface to the near-face zone for installation.

The lighting system which extends the length of the tunnel also must be extended at the rate of face advance. This requires transport and installation of high-voltage transmission cable, step-down transformers, low-voltage wiring, and mounting of insulators and brackets. Periodic inspection and replacement of incandescent bulbs must be made over the length of the tunnel.

Potable water is usually provided in portable tanks which must be advanced with the work zone and periodically removed for cleaning and refilling. Toilet facilities are self-contained chemical units which are periodically moved ahead with the work zone. Fresh chemicals must be supplied and waste removed, usually once per shift. An alternate method is the use of electric toilets which incinerate the waste and discharge into the exhaust air system.

All equipment used in excavation, ground support installation, project support, and materials handling must be properly maintained through an adequate preventive maintenance program if sustained rapid advance rates are to be achieved. Utilities, supplies, and spare parts required for operation of the equipment must be available when needed. Lighting power is usually provided from the same high-voltage transmission line used for equipment power. Water for cooling or hydraulic systems is provided from a high-pressure water line. Compressed air is usually piped in or may be obtained from local electric or diesel operated compressors. All utility lines must be extended at the same rate as the face advance, thus adding these construction materials to the quantities carried by the material handling system. Diesel fuel, lubricants, and compressed gases are usually provided in portable tanks or drums which must be transported to the work zone. Spare parts are too varied and specialized to be identified in generalities.

The miscellaneous support activities, with the exception of groundwater removal, are performed intermittently and do not add significantly to the load imposed on the material handling system. The requirement is primarily for personnel and special equipment transport to various points in the tunnel. Removal of groundwater from the tunnel requires a pipe and pump system separate from the industrial and cooling water system and having pickup points at frequent intervals if there is an appreciable amount of groundwater. The major impact of the miscellaneous support activities on the materials handling system is the requirement that it be able to stop and start from various locations in the tunnel complex without interfering with continuous operations.

Materials Handling

There are two basic functions to be performed by the materials handling system: removal from the tunnel complex of excavated material (muck) and transport of other materials, equipment, and personnel within the tunnel complex. Removal of muck requires:

- Loading onto a transport system
- Transport through the horizontal tunnel
- Lifting to the surface through a vertical shaft or through an inclined shaft or tunnel segment
- Transport on the surface from the collar or portal to the disposal site
- Unloading or dumping material from the transport system.

Depending on the particular mode of initial transport selected and the method of excavation used, processing of the muck prior to loading onto the transport system may be required to reduce the particle size of the muck or to change other of its characteristics such as temperature or water content. The mode or modes of transport also determine the need for transfers from one mode to another or processing at points of direction change.

Transport of other materials, equipment, and personnel requires considerable flexibility in the transport system to accommodate the wide variety of shapes, sizes, and masses to be transported. These factors are heavily influenced by the methods used for excavation and ground support. Regardless of the material characteristics and mode of transport, material must be:

- Loaded onto the system in the surface construction support area
- Moved to the portal or collar
- Lowered to the tunnel depth
- Transported through the tunnel to the near-face zone or other point of use
- Unloaded from the transport system
- Moved into position for installation or use

Processing of these materials such as changes in size and shape, or mixing of materials, is usually performed only in the surface support area or near the point of application. Transfer from one mode of transport to another may be required at points of direction change. A minimum of transfers is desirable, as each transfer adds to the cost of the material handling function.

The mechanisms used for loading, unloading, and transfer of materials must be compatible with the mode of transport used and the specific material being handled. Although these mechanisms are vital to the flow of materials, they normally are not major elements of cost where long distance transport is involved. Mechanisms for erection, installation, or application are highly specialized for the particular material and method being used and are, therefore, more appropriate for inclusion in an evaluation of ground support methods or other applications than in evaluation of material handling methods. The modes of horizontal and vertical transport are the major considerations in the comparison of alternate material handling systems.

The most frequently used mode of horizontal transport for tunneling projects is a form of conventional rail system with cars and locomotives designed to accommodate the space limitations and other adverse conditions encountered. Cable-operated skips are the most common mode of lift for vertical or steeply inclined transport. In underground excavation projects with only relatively short runs or where flexibility of transport is the overriding consideration, rubber-tired vehicles are often selected rather than or in conjunction with rail systems since they provide greater mobility and have the ability to climb somewhat steeper grades. These transport modes are usually fairly satisfactory for present-day requirements, because for most projects the pace of operations is determined by intermittent excavation or ground support installation activities which do not impose requirements on the material handling system beyond its capacity. As improvements are made in excavation techniques and ground support methods to increase the rate of face advance, the pace of all related operations must increase, thus requiring development of new material handling methods or improvements and adaptation of existing methods to the new requirements.

Several modes of material transport currently used in various types of industry have been suggested for adaptation to material handling for tunneling. These include pipeline systems, conveyor systems, cableway systems, and modifications of conventional and other rail systems such as monorails and siderails. These and other transport system concepts are described in Chapters 2 through 5 of this report.

The selection of a surface handling system for a project is strongly influenced by distance to the disposal point or point of origin of the material, topography of the area, purpose for which the material is to be used after discharge, and cost of the system. The muck removal system is also dependent on the nature of the material at the portal or shaft collar. For example, wet muck might require dewatering in order to be carried away effectively by a conveyor system, or dry muck would require slurry development to be removed by a pipeline. Costs for changing the state of materials to fit a particular mode of transport must be included in the cost of that mode when making a comparative evaluation. Current methods for surface transport of materials for underground workings are predominately truck or rail; although for some cases of very severe topography, these are supplemented with cableways or aerial tramways. For relatively short periods of use, as would be the case for surface transport servicing portals or shaft collars during construction of a long tunnel, the cost of civil works to provide rail or road transport could impose a severe cost penalty. Since the selection of surface transport systems is so highly dependent on the local topography and the availability of existing facilities in the vicinity, disposal of muck at the surface construction support area is used as a basis for comparison of alternate modes of material transport in the tunneling process.

Tunneling Process as a System

The tunneling process consists of four major functions:

- Excavation
- Tunnel structure installation
- Project support activities
- Materials handling.

To obtain rapid face advance at the heading, these four functions must be performed continuously and simultaneously, thus creating a high degree of interdependence among all operations. Each of the major functions can be further divided into subfunctions, and several alternate methods exist for performing each of the subfunctions. This increases the interdependence among operations, since the selection of method for performance of one function can influence the selection of an appropriate method for other functions. For example, the methods of excavation and ground support determine the characteristics of much of the material to be transported by the material handling system.

This integrated set of interrelated functions and operations together with the necessary mechanical hardware, structural components, and personnel can be thought of as a "total system" with the defined objective of producing a specified tunnel complex. This concept of the tunnel project as a "system" provides a useful analytical framework for consideration and evaluation of alternate methods of performance of the functions of the system, such as alternate modes of material transport. Attention is usually focused on a subsystem of the total system. The tunneling project system's hierarchy is summarized in Figure 1-3 where the major functions of the tunneling system and its primary subsystems are shown in rectangular boxes, and alternate items for performance of some of the functions are shown in oval boxes.

In defining a complex systems structure, arbitrary decisions must often be made regarding the system location of a particular function. For example, gathering muck from the tunnel floor at the face and removal from the face zone could be considered a function of the muck-removal system. However, because the mechanism used for this function is so closely related to the method used for fragmentation and/or removal of material from its position in the face, it is more appropriate to consider removal of muck from the face zone as part of the "remove in-situ material" system. In the case of mechanical moles, fragmentation and removal from the face zone are performed by the same mechanical system. A similar situation exists regarding the materials handling required to move into place and install components of the primary support and secondary liner systems. The mechanisms used are highly specialized and determined by the method of support or lining selected. Therefore, it is more appropriate to consider these mechanisms to be part of the tunnel structure installation system rather than the materials handling system.

A more detailed definition of the excavation system can be developed only after a specific method of excavation has been selected based on the existing ground conditions and the stage of development of the alternate methods at the time of selection. The rock or ground type and method of excavation determine the protection required in the face zone, the system required to advance the excavation system at the rate of face advance, and the characteristics of the muck produced. Selection of the excavation system determines the utilities, supplies, spare parts, and personnel required to operate and maintain it and the materials required for protection and advancing the excavation system. The characteristics of these materials are factors in determining requirements for the material handling system.

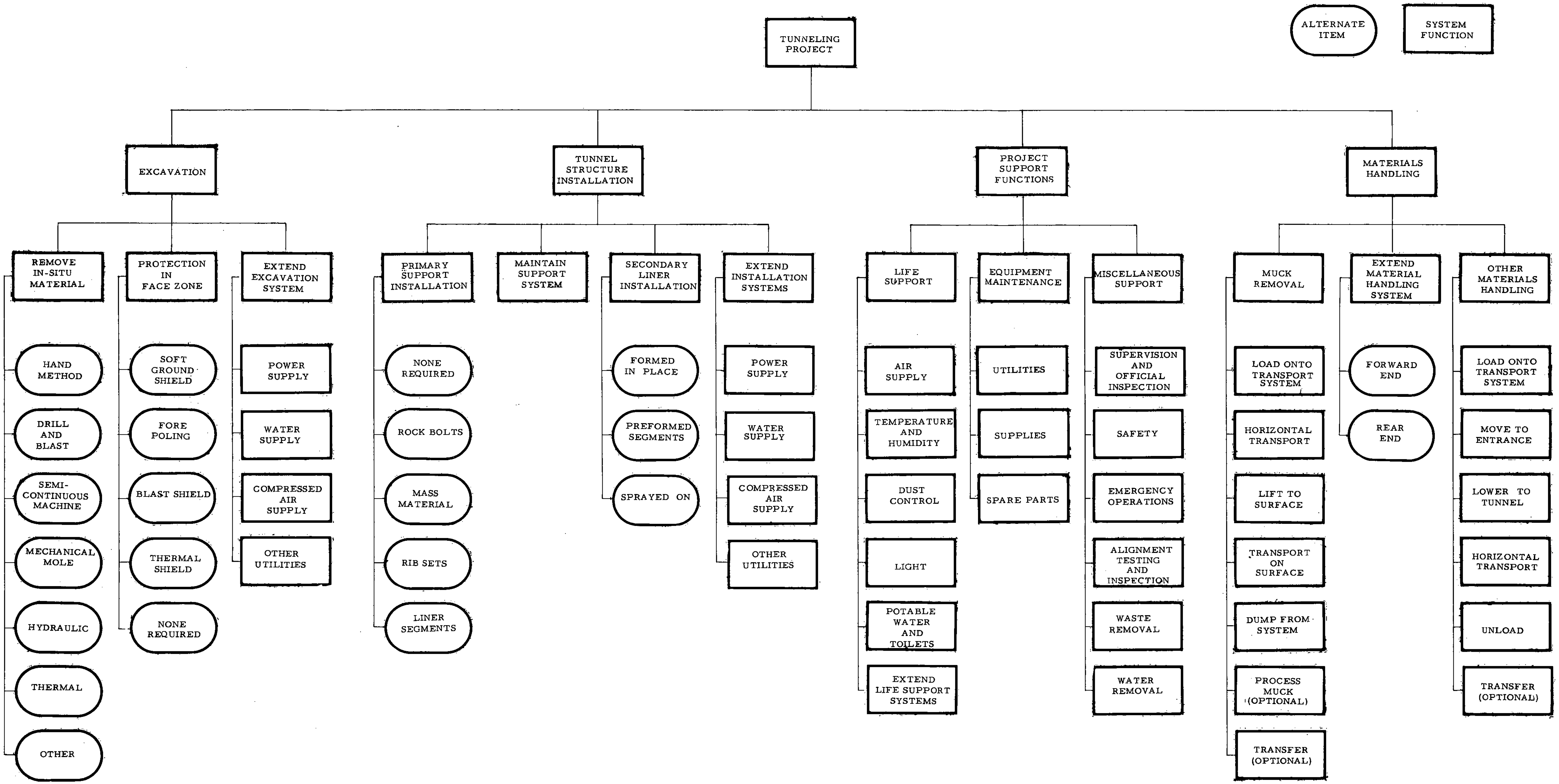

FIGURE 1-3

TUNNELING PROJECT SYSTEMS HIERARCHY

In like manner, the ground condition and stage of development of alternate primary support methods determine the selection of support method, or combinations of methods, and the maintenance required for the support system. The selection of primary support method determines the equipment and personnel required for installation. The equipment selection determines the utilities, supplies, and spare parts required for equipment maintenance and materials required to extend the installation system. Similar logic can be outlined for the secondary liner installation. The materials required for tunnel structure installation equipment maintenance, advance of the installation system, and as components of the structural system at the time of installation and for maintenance are major factors in determining requirements for the material handling system.

Project support functions can be grouped into life support, equipment maintenance, and miscellaneous support. Although materials such as air, water, electricity, and compressed air are required, they are normally supplied through ducts, pipes, or cables not normally considered to be part of the material handling system. Removal of groundwater also is usually handled by an independent pumping system. Other materials such as supplies, spare parts, and materials required to advance pipes, ducts, and cables must be transported by the material handling system. Personnel required for all operations, maintenance, and miscellaneous support activities also must be transported by the material handling system.

The material handling system or systems perform the functions of loading, horizontal transport, change of elevation, and dumping or unloading. In addition, the optional functions of processing and/or transfer may be performed depending on the selection of modes of transport and the compatibility of the materials with the modes selected. Several alternate methods can be identified for accomplishing each of these functions.

The selection of a particular method or combination of methods in conjunction with the quantities of materials to be handled determines the space requirements for the material handling system and the materials required to advance the system in the near-face zone. For some modes of transport, the system advance materials may be a major factor in determining the requirements for the material handling system.

For a generalized comparative evaluation of material transport modes, which is the purpose of this study, extreme detail in the identification of alternate methods and elements of the tunneling project system is not necessary as long as the characteristics of all types of material and the approximate quantities of the major types are defined.

IMPLICATIONS OF TUNNEL GEOMETRY

Basic Configuration

Two general types of tunnels are considered: portal tunnels and deep tunnels. Both of these types are shown schematically in Figure 1-4. A portal tunnel generally enters the inclined or vertical face of a mountain or ridge and passes more or less horizontally through to the other side. There is no significant change in the elevation of materials during transport inside the tunnel. For evaluation of material transport systems, this situation is the same as transport through a horizontal or slightly inclined segment of a deep tunnel.

A deep tunnel, which may vary in depth from just below the practical limit for cut-and-cover excavation to 3, 500 feet for this study, requires major changes in the elevation of materials transported in the tunnel complex between the surface and the deep tunnel. For long tunnels where the distance between portals (stage length) may vary from 20 to 450 miles, as is assumed for this study, intermediate shafts will be required for ventilation and access during construction and operational use of the tunnel. These shafts may be vertical or inclined as determined by an economic balance between various cost trade-offs for a specific ground condition and topography. The parametric range of shaft spacing assumed for this study is 5 to 20 miles

The relationship between vertical, horizontal, and slant distances for various degrees of incline of shafts and various grades in tunnels is shown in Figure 1-5. Due to limitations imposed by the assumed use of the tunnel, grades for tunnel segments are restricted to less than 26 percent. In this range of grades for a tunnel depth of 3, 500 feet, the slant distance of the inclined tunnel segment is about 13 miles for a 5-percent grade and less than 3 miles for a 26-percent grade. For a depth of 500 feet, the slant distance varies between 2 miles and less than 0.5 miles. Thus, for short stage lengths the entire tunnel may consist of two inclined segments; while for long stage lengths, the inclined segments of the tunnel may be about 1 percent of the total tunnel length at depths of 3, 500 feet and less than 0.1 percent at depths less than 350 feet.

Tunnel bore diameters fall in the range of 10 to 40 feet, and the heading advance rates are assumed to vary from 300 feet per 24-hour day to 1, 500 feet per day to assure inclusion of average rates considered to be achievable within the next 20 years.

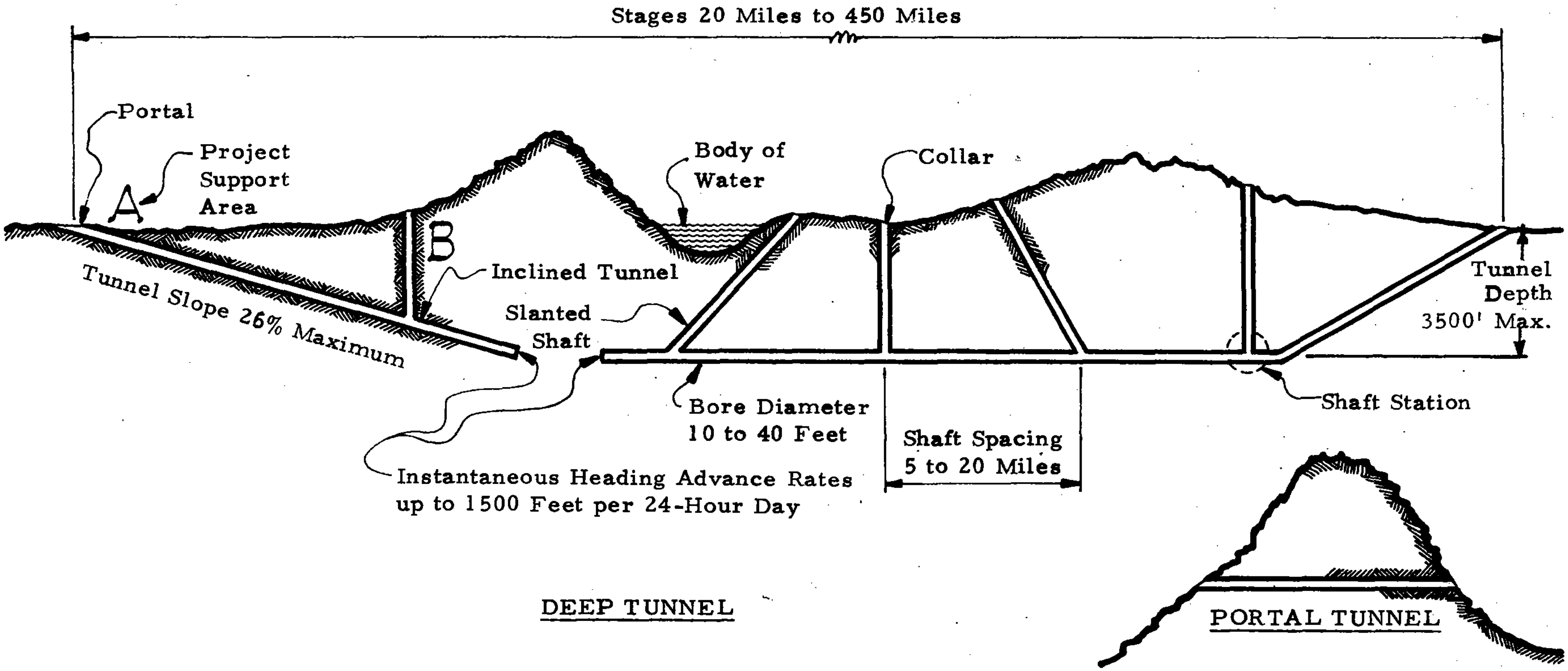

FIGURE 1-4

TUNNEL GEOMETRY

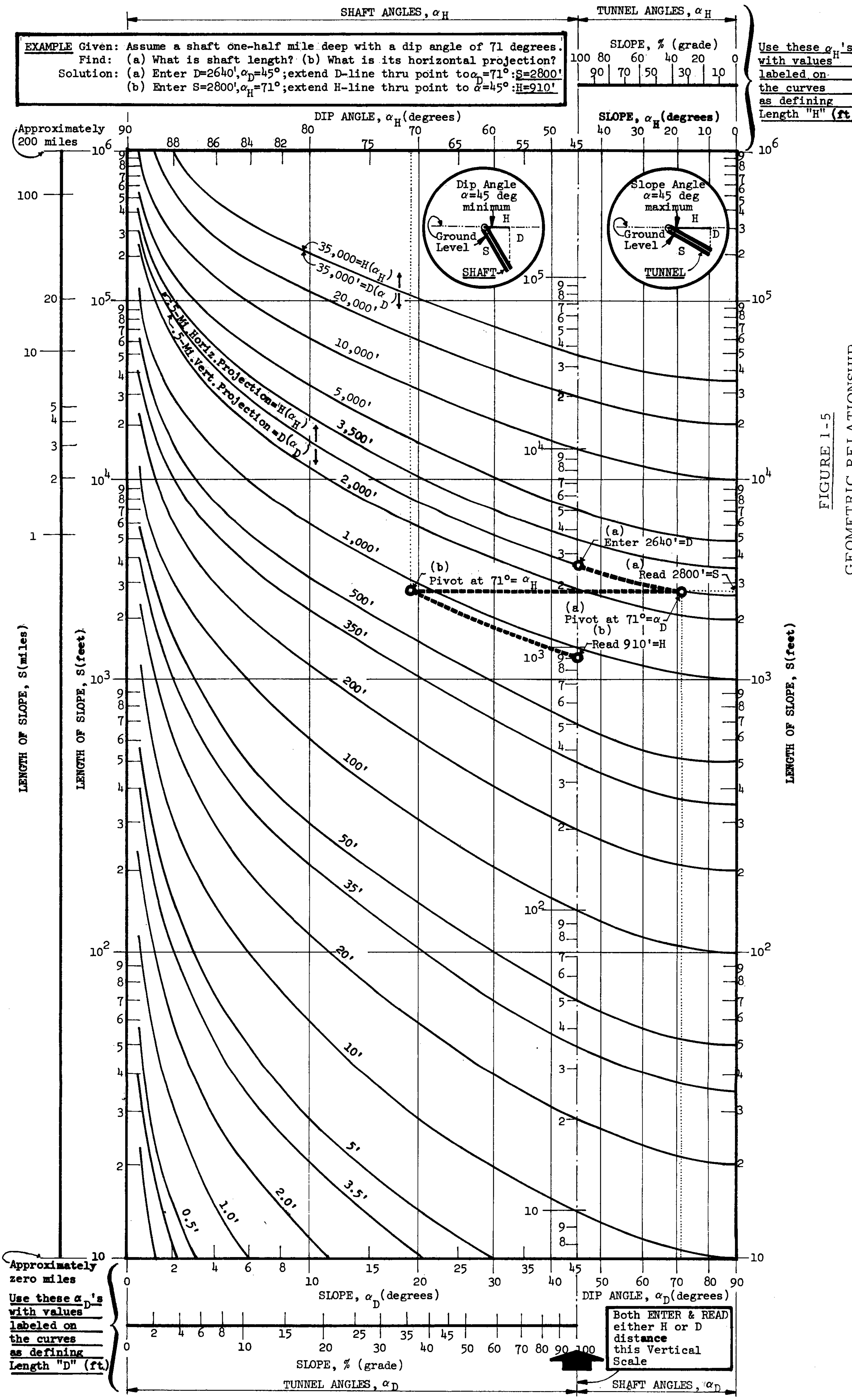

FIGURE 1-5
GEOMETRIC RELATIONSHIP FOR INCLINED TUNNELS AND SLANTED SHAFTS

Figure 1-6 shows a comparison between volumes of muck removed from the tunnel and that removed from the shafts for tunnel complexes within these parametric ranges. It can be determined from this graph that for the maximum tunnel depth of 3, 500 feet, the material removed from the total shafts is 13 percent of that removed from the tunnel for minimum shaft spacing and 3 percent for maximum shaft spacing if shafts are assumed to have the same diameter as the tunnel. For a tunnel 350 feet deep, the proportion would vary from 1. 3 to 0. 3 percent. To illustrate the use of Figure 1-6, consider the following example:

- Assume that a 30-foot diameter tunnel is to be driven 100 miles at a depth of 3, 500 feet with shaft spacing of 5 miles and that there are three 10-foot shafts at each shaft location. The total number of shafts would be 57.
- For a tunnel length of 100 miles and a diameter of 30 feet, read 24. 2 million cubic yards of muck based on a swell factor of 1. 75.
- For a shaft depth of 3, 500 feet, a diameter of 10 feet each, and a total of 57 shafts, read 1. 5 million cubic yards of total shaft muck.
- Comparing shaft muck volume to tunnel muck volume, observe that the total shaft muck is less than 10 percent of the tunnel muck.

Figure 1-7 presents the tunnel project duration for various tunnel lengths and heading advance rates. It can be observed that a 100-mile tunnel driven at one heading, advancing at an average rate of 500 feet per 24-hour day, would require about 4. 5 years to complete if 20 work days per month are assumed. The time required for geological exploration, ground preparation, shaft sinking, setup and dismantling of equipment, or other preparatory activities is not included in this estimate. Obviously, if four headings were advanced simultaneously at the same rate, the project duration would theoretically be reduced to approximately 1 year.

For a 20-mile tunnel advanced at the rate of 750 feet per day, 140 days are required. If 20 days are required for equipment setup and 10 days for dismantling, the nonproductive portion of the cycle is greater than 20 percent of the productive portion. This would represent a significant increase in the cost per foot of advance and illustrates the desirability of long, continuous runs once a heading has been established.

Referring to Figure 1-4, one can observe that if during construction of the inclined segment of the tunnel the project is supported from project support area A at the portal, and as the heading passes the first shaft station it is desired to support the excavation activity through shaft B,

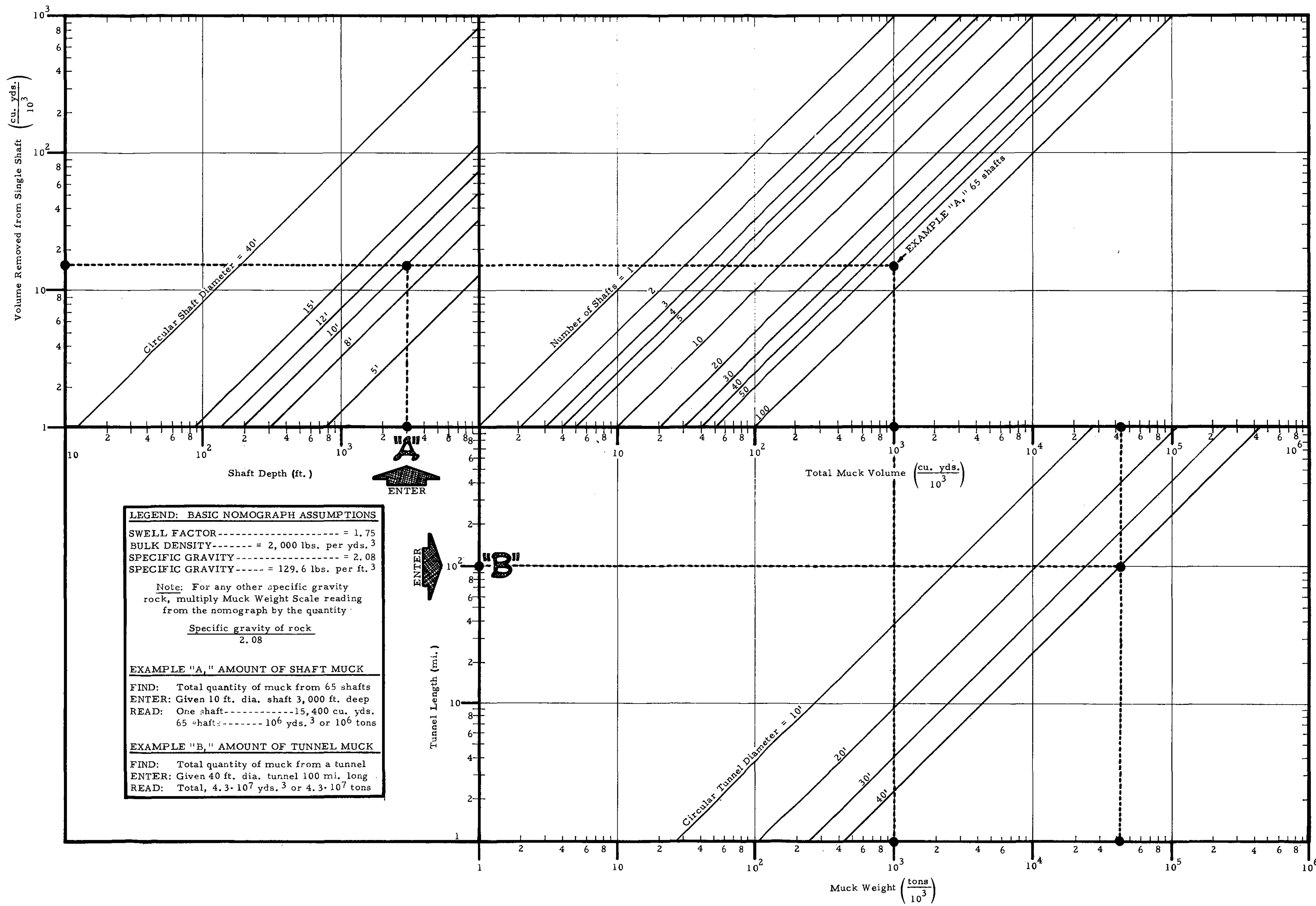

FIGURE 1-6

MUCK QUANTITIES

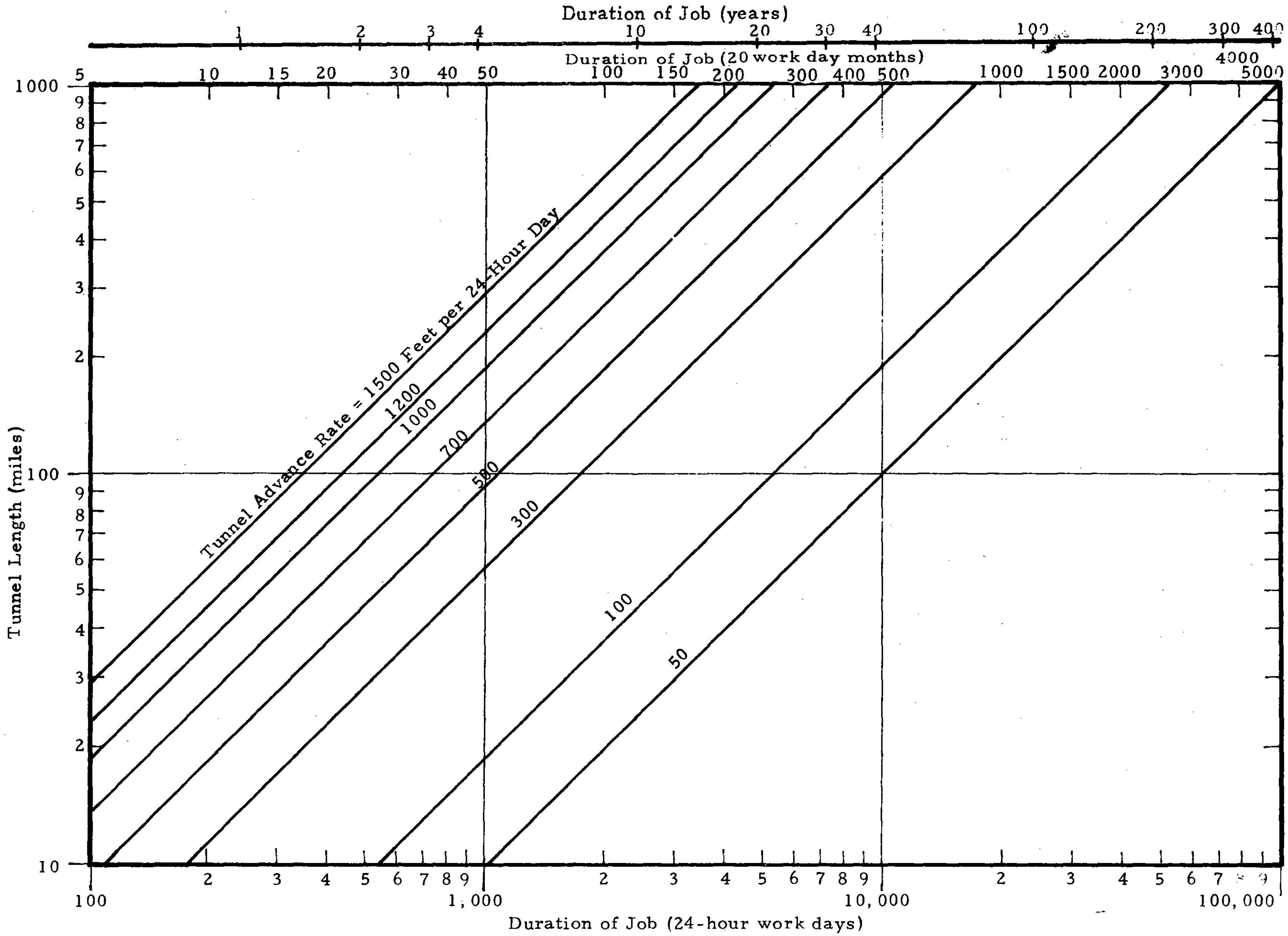

FIGURE 1-7

TUNNEL PROJECT DURATION

it is necessary either to move the project support area to the collar of shaft B and surface transport materials to it at the new location, or leave the support area at A and transport materials on the surface between positions A and B. For some topographic situations, either of these alternatives could become major cost factors.

Material Handling Situations

Due to the basic tunnel configuration under consideration, a limited number of material handling situations is possible. These are shown in Figure 1-8. There are three major flows of materials: outward flow of muck from the face zone, inward flow of materials and personnel to the near-face zone, and outward flow of waste and personnel from the near-face zone. In addition, material (including personnel) may be loaded onto or discharged from the transport system at intermediate points between the terminals of the system.

Situation "A" occurs when excavation is started at a portal and the inclined tunnel is driven downward to the point where a transition to the horizontal tunnel occurs and the advancing face continues to move forward. In this situation, the only possible route for material transport is through the horizontal and inclined segments of the tunnel.

After the advancing face passes the location of a previously constructed shaft, an alternate path is provided for material transport. As shown in Sketches "B", "C", and "D", three possibilities exist.

- Muck can be transported along the tunnel to the shaft while other materials are moved through the tunnel to and from the portal.
- Muck can be moved out through the tunnel to the portal while other materials are lifted and lowered through the shaft.
- Muck and all other materials can use the shaft for entrance to and exit from the tunnel.

Sinking a shaft ahead of the tunnel advance is shown at S_2 in Sketch "C." Material handling for this situation is entirely independent of the tunneling process and is, therefore, not considered in this study.

Situation "E" would occur in a short tunnel with no shafts as an extension of situation "A". In this case, the face is advanced upward; and all material is transported on an incline at both ends of its journey.

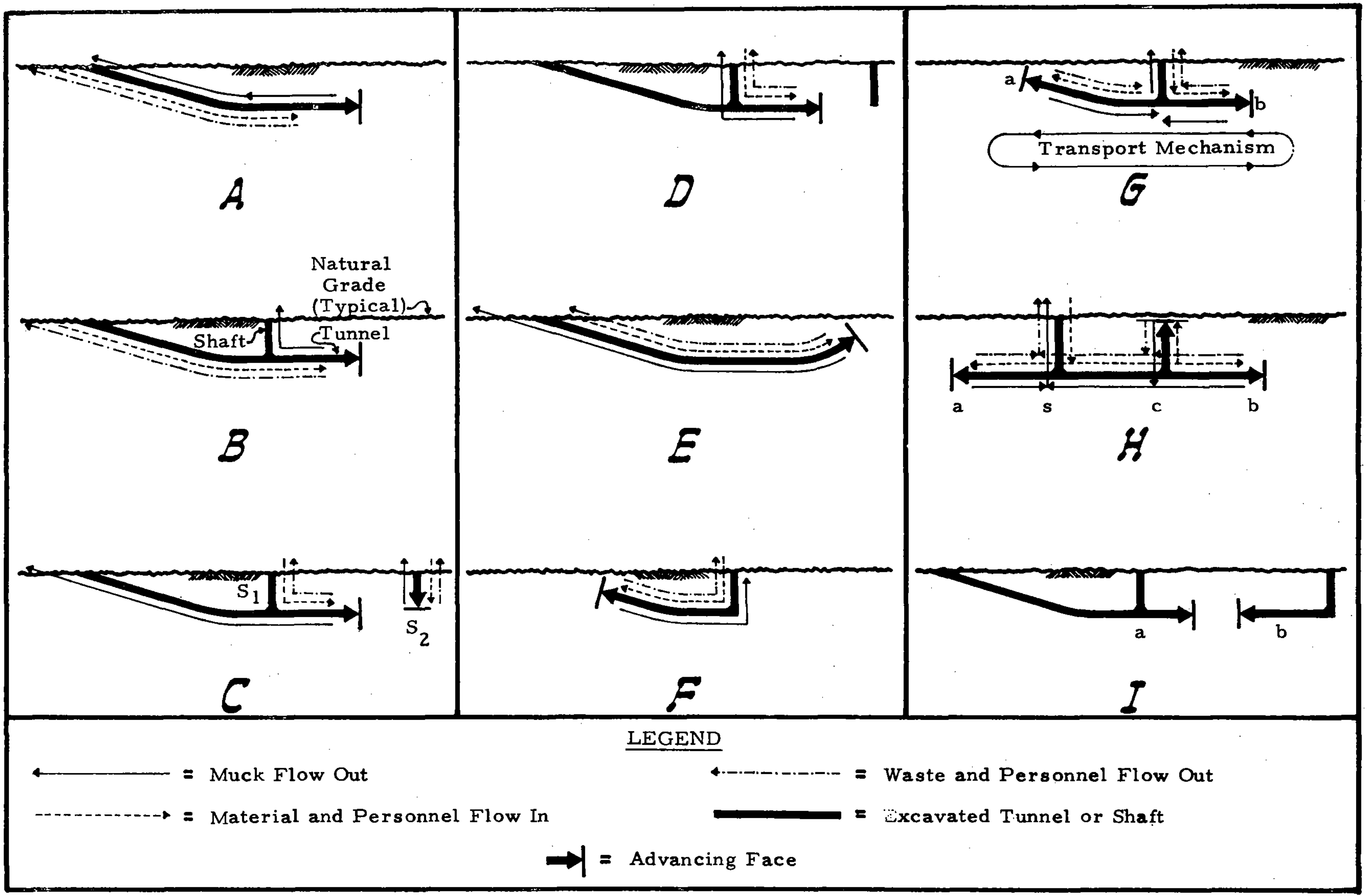

FIGURE 1-8

MATERIAL HANDLING SITUATIONS

Situation "F" would result from face advance in "E" passing a previously constructed shaft prior to starting up the tunnel incline or from sinking a shaft to provide access to the tunnel depth for raise boring of the inclined tunnel segment. If face advance in "E" had passed a previously constructed shaft, then any of the situations in "B", "C", or "D" could occur with the modification of raise excavation of the tunnel as shown in "E" and "F".

If situation "D" is combined with situation "F", the situation shown in "G" is obtained. This offers the possibility of a transport mechanism or mechanisms shuttling between faces "a" and "b" with automated loading and unloading on the fly at the shaft station. One apparent disadvantage in this situation is the heavy traffic burden placed on the shaft and shaft station. If the face at "a" is in a horizontal tunnel segment rather than inclined as shown, the situation remains essentially the same.

Situation "H" is essentially the same as "G" but with the added complications of raise boring of a shaft over a segment of tunnel at point "c". Although this situation offers the possibility of shuttling between faces "a" and "b" as in situation "G", it would require onloading and offloading at two points along the flight. The segment of the transport system between points "s" and "c" would be required to carry a double load, and the shaft station and shaft at "s" would carry a triple load. Multiple headings serviced by a single access as shown in this situation appear to compound an already difficult problem.

The situation in "I" is a combination of "B" or "C" with "D". It illustrates the problem created by advancing two headings toward each other. When they meet, it will be necessary to back out all the equipment and transport it to a new working face. This could be a major cost factor.

Any other material handling situations which can be visualized will be combinations, portions, or slight modifications of the situations shown in Sketches "A" through "H".

Tunnel Cross Section

The size and shape of the tunnel cross section or bore configuration is determined initially from the intended use and nature of the ground to be penetrated. The bore configuration establishes the volume of muck to be removed, the exposed surface area requiring structural support and lining (which establishes the quantity of construction materials), and the space available for material handling systems and other construction activities.

The most common bore configurations are circular, horseshoe, and vertical sidewall. These basic configurations are shown in Figure 1-9. It is apparent that for equivalent diameter sections (D = 2R = R + h) the volume of muck removed and surface area exposed is the least for a circular section and the most for the vertical-sidewall section, with the horseshoe falling between the extremes. It is also apparent that the usable floor area becomes greater as the configuration goes from circular to vertical sidewall. This in turn provides better utilization of the total cross section for transport of wide loads requiring head room.

Modifications of the vertical sidewall are sometimes used by increasing h to produce a high sidewall configuration or increasing W which results in a configuration referred to as the basket handle. Since the circular and vertical sidewall configurations present material handling problems, each typical of other similar configurations, only these two are considered in this study.

Figure 1-9 also indicates three possibilities for an underground transportation tunnel complex. Two-way traffic and all service functions could be placed in a single large tunnel bore; two smaller tunnels could be used, each to carry one-way traffic with its own service support; or the service support could be centralized in a third service tunnel supporting both of the one-way traffic tunnels. The only impact on the evaluation of material handling methods posed by the number of tunnels in the complex is that due to the change of tunnel diameter. This study considers single tunnel bores varying in diameter from 10 to 40 feet.

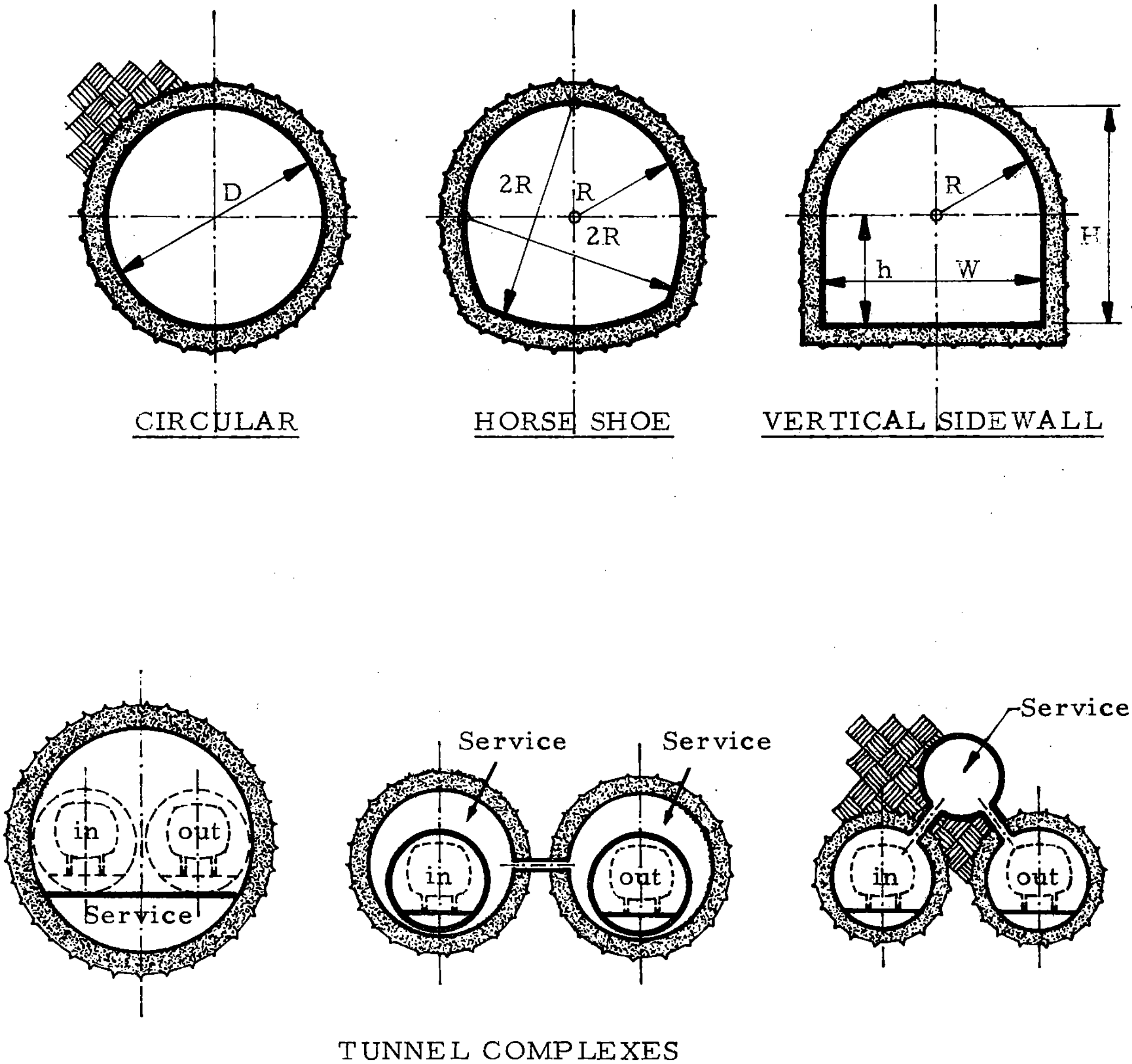

FIGURE 1-9

TUNNEL CROSS SECTIONS

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CHAPTER 2

MATERIAL HANDLING SYSTEMS

FUNCTIONAL ELEMENTS

In Chapter 1 the tunneling process is discussed briefly and defined as an integrated system consisting of four major functions: excavation, ground support, project support, and materials handling. The materials handling function for deep tunnels includes the following elements or operations:

- Gathering and loading items or substances onto the material transport system.
- Transport through the horizontal tunnel and on the surface.
- Transport through shafts or inclined tunnel segments involving changes of elevation between the tunnel and the surface.
- Transfer of materials from one mode of transport to another.
- Unloading items or substances from the material transport system.
- Storage of materials in a slow-moving queue or as stationary substances waiting to be used or transported.
- Moving materials or components into position for installation or application.
- Packaging or consolidation of a number of items or a quantity of a substance to facilitate handling.
- Processing (changes in nature or form) of a substance required for the material to be compatible with a particular material handling system.

TYPES OF MATERIALS

The performance of each of the major functions of the tunneling process produces and/or uses materials which must be transported and otherwise handled within the tunnel complex. The term "materials," in the broadest sense, refers to all items or substances such as men, equipment, construction materials, supplies, and waste materials involved in the tunneling process. Construction materials include those required for installation of ground support and for extension or advance of all service lines and material handling systems as the excavation face moves forward. A representative list of these materials or substances, which are identified in greater detail in Chapters 6 through 11, would include:

- Men or work crews for excavation, installation of ground support, extension of service lines and material handling systems, operation of material handling system components, and performance of project support functions including maintenance of all equipment and ground support systems and removal of waste materials.

- Equipment such as transformers, pumps, blowers, mixers, crushers, compressors, welders, rock drills, test and inspection equipment, and equipment for atmospheric control.

- Equipment for loading, unloading, and transfer of materials in the material handling process.

- Highly specialized equipment for erection, installation, and/or application of ground support systems.

- Equipment for handling and installation of extension components for the material handling systems and service lines.

- Materials and supplies such as drill bits, cutter heads, and explosives used in the excavation operations.

- Materials and supplies such as spare parts, fuel, lubricants, and compressed gases required for operation and maintenance of all equipment.

- Components and materials such as rock bolts, wire mesh, metal plates and shapes, sand, gravel, cement, reinforcing bars, perforated sheet metal, structural steel, wood blocks and timbers, and precast reinforced concrete components which are used in construction of the primary and secondary ground support systems.

- Components and materials such as ducting, pipe, high voltage transmission cable, high pressure hose, electrical wiring, insulators, brackets, and fittings required to extend all service lines.

- Components, materials, and spare parts for extension and maintenance of the material transport system. The specific materials required are determined by the particular mode of transport used. Typical examples include structural steel components, pipe or ducting, conveyor belts, support brackets and anchors, rails, ballast, timber or concrete cross ties, cables, gears, bearings, wheels, and rollers.

- Waste material such as muck or spoil produced by the excavation operation, ground water which seeps or flows into the tunnel, human waste, wastage or discarded materials from installation of ground support and other operations, and discarded packaging materials and containers used for transporting materials.

Although all of these materials probably would not be required simultaneously for a particular tunneling project, the list is indicative of the large variety of materials which the material handling system may be required to transport. The specific materials used for a tunneling project are determined by the methods being used for excavation, ground support, and material handling. On a large, complex project more than one method may be used for each function at some point in the project, thus imposing a wide range of materials on the transport system.

BOUNDARIES OF MATERIAL HANDLING SYSTEM

Factors, which are discussed in Chapters 1 and 6, bearing on the extent and boundaries of the material handling system under consideration may be summarized as follows:

- Services and service materials such as electric power, air, water, and compressed air are normally supplied through separate ducts, pipes, or cables which are not considered to be part of the material handling system of concern. The only impact of these service supply systems on the material handling system is the space which they occupy and the fact that the materials required to extend the service system must be transported by the material handling system.

- Groundwater removal is usually accomplished by means of an independent pipe or hose system which is not considered to be part of the material handling system of concern. The material handling system must transport the materials and equipment required for extension of the groundwater removal system.

- The material handling system used during shaft sinking is not a part of the material handling system of concern because shaft sinking and tunnel face advance are entirely independent of each other, except in the case of raise boring of a shaft which imposes an additional load on the material handling system used for tunneling.

- Long-haul transport aboveground is excluded from consideration due to its dependence on local topography and other surface considerations.

- Material handling required for erection, installation, or application of materials and components is excluded from the system of concern. The mechanisms used for these operations are usually highly specialized to the materials and methods used and are more appropriately included in an evaluation of the specific operation rather than an evaluation of the material handling system.

- Gathering, consolidation, or packaging of materials is not included in the system of concern since the need for these functions is determined primarily by the nature of the material rather than by the mode of transport.

- Loading, unloading, and transfer mechanisms which must be compatible with the mode of transport and material being handled are normally not major cost elements in long-haul transport systems. They are included as cost elements in the system of concern, but alternate methods are not evaluated.

- Processing is included as a cost element of the material handling system when required for a particular mode of transport, but alternate processing equipment is not evaluated.

- Intermittent or temporary storage of materials is considered only qualitatively in recognition of the fact that some transport modes more adequately provide this function than others.

Considering these factors, the material handling system of concern is defined as the hardware system required to transport all substances (not carried by independent service lines) that move between the surface construction support area and the underground work zones. The items of primary and secondary consideration are listed in Table 2-1.

TABLE 2-1

EMPHASIS OF MATERIAL HANDLING SYSTEM EVALUATION

Primary Emphasis	Secondary Emphasis	Excluded
Continuous Flow Materials:	Intermittent Flow Materials:	Service Requirements:
Muck	Personnel	Power
Ground Support Materials	Equipment	Ventilation
Materials for Systems Extension	Supplies and Spare Parts	Water
Material Transport System	Discarded Material and Other Waste	Compressed Air
Service Lines		Groundwater Removal
Long-Haul Transport	Short-Haul Equipment	In-Shaft Transport During Shaft Sinking
In Horizontal Tunnel	Intermode Transfer	
In Inclined Tunnel	Loading	Surface Transport
In Shaft	Unloading	Erection, Installation, and Application of Materials
Vertical	Processing	
Inclined	Storage	Gathering, Consolidation, or Packaging Materials

The continuous flow materials - muck, ground support materials, and materials for systems extension - are discussed in detail in Chapters 7, 8, and 9, respectively. The intermittent flow materials - personnel, equipment, supplies, parts, and waste - are discussed in Chapters 10 and 11.

The material handling system of concern consists of long-haul transport (one or more modes may be used) and auxiliary equipment for intermode transfer, loading, unloading, processing when required by a specific mode of transport, and storage represented by a slow moving queue. Comparative evaluation is focused on various types of long-haul transport systems.

TRANSPORT SYSTEM TYPES

System Requirements

A material transport system, which may consist of one or more modes of transport for a tunneling project, must satisfy many requirements imposed by the nature of the materials to be moved between the surface and the work zones and by the characteristics of flow required for these materials. For example, the material transport system must:

- Be capable of transporting bulk materials with wide ranges of characteristics including particle sizes from fine clays and sands through gravel to occasional large blocks and slabs; cohesiveness from dry free-flowing material to muddy or sticky wet material; particle size distributions in a given batch from nearly uniform to very wide ranges of particle sizes; and other properties from hard, sharp, abrasive particles to easily friable lumps.

- Be capable of transporting discrete items of material ranging from small pieces, which may be packaged into larger units, to large components weighing several tons each and covering a wide range of shapes and sizes, sometimes having a dimension greater than ten feet.

- Be capable of transporting equipment since there is a high probability that all equipment required for underground operations will need to be transported in disassembled or assembled form by at least the vertical or inclined portions of the material handling system, and intermittently used equipment may be returned to a shaft station or to the surface for storage or repair.

- Be satisfactory for safe transport of personnel.
- Be capable of transport through horizontal and vertical or inclined zones.
- Be compatible with the limited cross section and single route access provided by the tunneling project.
- Be compatible with other simultaneous activities such as ground support system installation, movement of self-powered equipment, and project support activities occurring in the work zones.
- Provide flexibility to accommodate more than one method of excavation and ground support within a given tunnel segment.
- Provide simultaneous and continuous inbound and outbound flow of materials.
- Economically sustain the minimum flow rate determined by the rate of excavation and respond quickly to variations in flow rate due to changes in the face advance rate, since space for surge storage is very limited and continuous flow must be maintained.
- Accommodate onloading and offloading at intermediate points to provide personnel, parts, and supplies for miscellaneous support functions; for pickup of discarded and waste material for disposal; and to move materials from an intermediate location in the tunnel to a forward location.
- Provide good reliability to minimize job shutdown due to material handling system breakdown, since only very limited amounts of material can be stockpiled at the in-tunnel work zones and inoperative equipment often cannot be bypassed.
- Be capable of continuous extension of system length in pace with the advancing excavation face.

A summary listing of these system performance requirements is provided in Table 2-2.

Hierarchy of Transport Systems

In seeking candidate systems for transport of materials in a tunneling project, many modes of transport may be considered to find the simplest and least expensive scheme that meets the performance requirements.

TABLE 2-2

TRANSPORT SYSTEM PERFORMANCE REQUIREMENTS

Material to be Transported	Environment-Related Factors	Material Flow Characteristics	System Extension
Bulk Materials Discrete Items Equipment Personnel	Horizontal and vertical or inclined transport Compatibility with limited cross-sectional area Simultaneous and continuous bi-directional flow over single route Compatibility with other tunneling functions	Accommodate wide variation in flow rates On-loading and off-loading at intermediate points High availability to provide continuity of flow	Continuous with minimum or no interruption of material flow.

Any transport method has four fundamental elements, which are:

- A medium or vehicle to give mobility to the material or payload being transported. Examples: the belt of a conveyor, the fluid in a pipeline transporting solids, the modules or cars of a rail system.

- A means of supporting the vehicle weight and the dynamic forces resulting from its movement. Examples: the supporting framework of a conveyor, the pipe and supporting structure of a pipeline, the railway or guideway of a rail system.

- A means of providing propulsive force to the vehicle. Braking forces also are required if the vehicle must reduce speed for loading or unloading material. Examples: a rotating wheel, sprocket or drum for a conveyor, a pump for a pipeline, a locomotive for a rail system, the motor in a self-propelled vehicle.

- A means of providing guidance of the vehicle along the desired path. Examples: the supporting structure for a conveyor, the pipe in a pipeline system, the rails and flanged wheels of a railroad, the operator of a truck.

The alternate possibilities for the mode or modes of transport can be categorized by these fundamental elements to identify more clearly their basic similarities and differences. Figure 2-1 shows a structured relationship or hierarchy for the more likely candidate systems for application to transport in a tunneling project. Several additional specific examples could be cited, but upon examination they appear to be further subdivisions or variations of those shown, or they appear to be unworthy of serious consideration for the application of concern.

Two major categories of systems are identified based on the flow characteristic of the payload and the conveying medium. In continuous flow systems the medium generally moves as a continuous stream in a closed loop and payload material is continuously added to and removed from the moving stream at the loading point and destination, respectively. In unitized flow systems the transporting medium is divided into mechanical modules or vehicles which subdivide the payload into discrete units of material. These modules may travel individually or be linked together to form a train. If a series of trains were to operate with no separation between trains and move continuously around a closed loop track with loading and unloading while in motion, the unitized system might be considered to be a hybrid form of continuous system. However, it is more appropriate to class this scheme with the unitized systems because modules or complete train

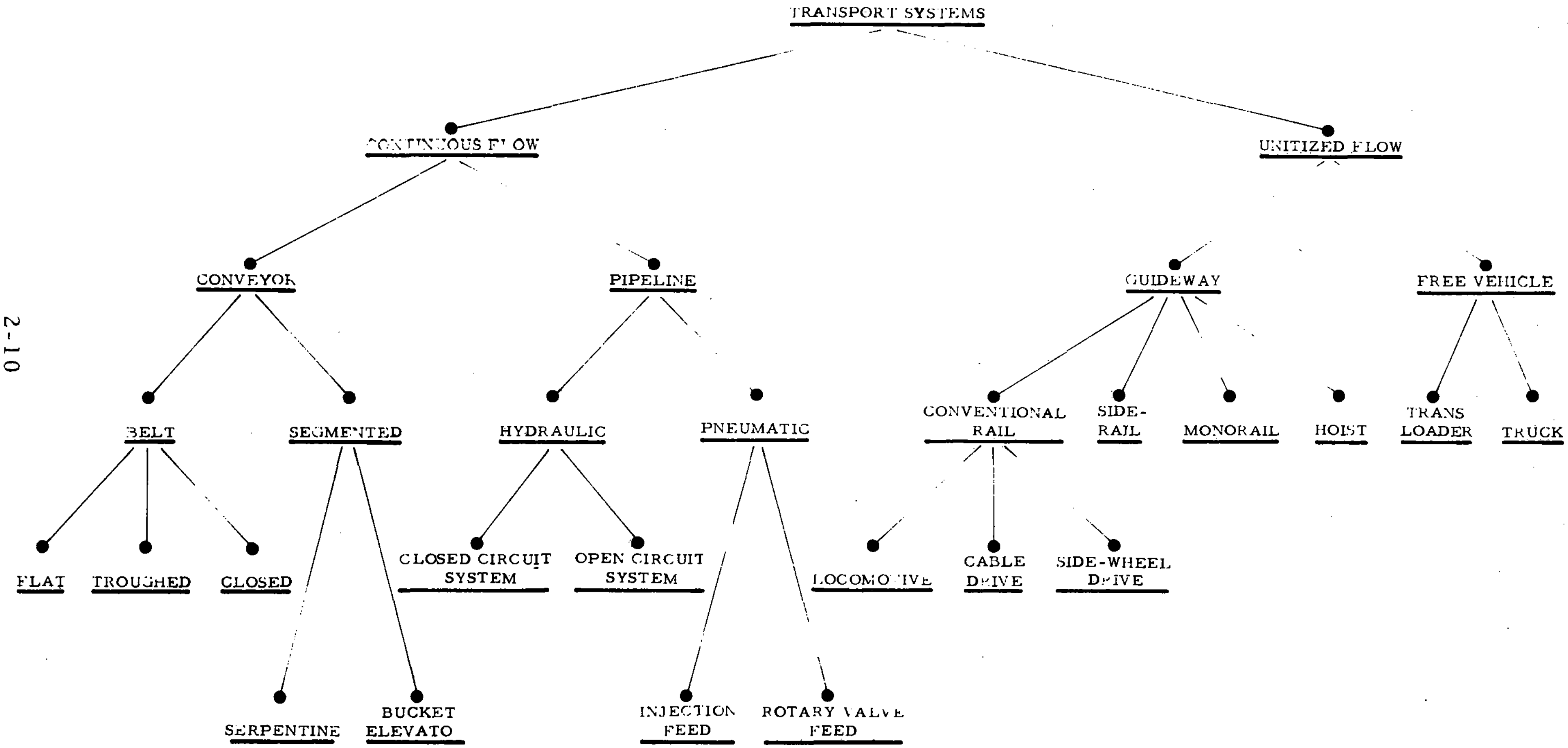

FIGURE 2-1

HIERARCHY OF TRANSPORT SYSTEMS

units can be removed from the moving loop and replaced without disrupting operation of the remainder of the system. This is not a characteristic of the continuous flow systems.

Continuous flow systems which are discussed in Chapter 3 can be divided into two types:

- Conveyors, in which the transporting medium is a mechanical device; and
- Pipelines, in which the medium is a fluid such as water or air.

The distinguishing characteristic of conveyors is that the mechanical transporting medium, often some variation of a belt, forms a continuously moving closed loop usually driven by a rotating pulley, sprocket, or drum at only one point in the loop. The belt loop, extending from the idler or tail pulley at the loading end to the drive or head pulley at the discharge end constitutes a single flight. The length of a single flight is limited by the load carried, the strength of the belt, and the traction between the drive pulley and the belt. Several flights may be used in series to extend the travel distance. The angle of ascent of a belt conveyor is limited by the tendency of the payload material to slip on the belt. The load per unit length of belt is limited by the angle of repose of the material and the belt strength.

Several modifications have been used to enhance the capability of conveyors. The edges of flat belts have been turned upward forming a trough to increase the load capability, or the edges have been brought together over the top of the material forming a closed tube to hold the material on the belt at high speeds or steep angles of ascent. Belts have been convoluted or stops or pockets added to the surface to segment the payload and increase the permissible angle of ascent. Belts are reinforced or supported by cables to increase their strength. Chain supporting the belt and driven by sprockets may be used to increase traction. A novel suggestion(1) to overcome the limitations of the single point drive is the development of a linear induction motor belt conveyor. Another suggestion for improved performance of a troughed belt conveyor, described in the same reference, is the use of an air cushion to provide continuous support of the belt thus reducing belt tension and wear.

For vertical or near vertical lift the belt has been completely segmented to form containers or buckets attached to a chain or cable support. As the angle of ascent increases a larger portion of the weight of the belt and the payload must be supported by the head pulley until, in the vertical case, the entire weight is supported at this single point. This limits the practical height of hoisting by a conveyor type system.

Support and guidance of a conveyor system is provided by a structural framework and idler rollers which keep the belt in a predetermined path. This path normally cannot make sharp changes of direction or angle of incline and maintain proper operation of the belt. The serpentine concept* has overcome the limitation to a large extent by the use of convolutions in the belt and rollers which travel with the belt in a confining guideway.

Based on these modifications of the basic conveyor concept, conveyor systems can be categorized as belt conveyors with flat, troughed, or closed belts or as segmented conveyors represented by the serpentine or convoluted belt conveyor and the bucket elevator.

Pipeline systems can be classified as hydraulic or pneumatic, based on the type of fluid used for the transporting vehicle. The fluid stream moves in a closed loop, although in some cases this is not readily apparent. For example, in the case of a hydraulic slurry pipeline using an abundant water source at the input end and discharging without recirculation, the closed loop is formed by the replenishment of the water source through some path of nature. A pneumatic system usually operates through a single pipe depending upon the normal flow of air for the return path. In a tunneling application, the tunnel would provide the return pipeline, thus providing tunnel ventilation as an added benefit. In the absence of an abundant supply of water, a hydraulic system would require two pipelines over the entire route to carry the slurry and to return the water stream for reloading with payload material.

The moving stream in a pipeline system is propelled by the pressure differential provided by a pump (usually called a blower or compressor in the pneumatic case) or series of pumps. This source of motive power can be at a single location in the system or as booster pumps at several locations. Another possible arrangement to extend the range of the system is to operate more than one loop in series, feeding material from one loop to the next. The preferred scheme is dependent upon the particular situation.

In pipeline systems, the pipe provides both guidance and support for the payload and conveying vehicle. The pipe may be placed directly on the ground or supported by hangers or racks as desired. Precise alignment is usually not a critical factor for pipeline systems.

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*Developed as the Serpentix by the Serpentix Conveyor Corporation, Denver, Colorado.

Unitized flow systems which are discussed in Chapter 4 are classified by the guidance method as

- Guideway systems, in which vehicles or modules travel on steel or concrete rails or other guiding structural elements, and
- Free vehicle systems, in which self-propelled vehicles or trains are guided individually through any acceptable path on a suitable surface.

Free vehicle systems have maximum flexibility in regard to their travel path, but this is paid for through increased cost for operators or complex remote guidance systems. Although free vehicles can be operated as trains to reduce operator cost, this appears impractical in the confined space of the tunnel environment. The increased flexibility of the free vehicle is of questionable value in the confined space and single-route access provided by a tunnel. Free vehicles which appear to have some possible merit for a tunneling project are designated as transloaders suitable for short-haul applications and trucks for longer-haul situations.

Another form of free vehicle, known as "ground effect machines" or "hovercraft," is the air cushion vehicle (ACV) which lifts itself a short distance above the running surface by a fan-generated cushion of air. Much development work on this concept has taken place in the past ten years to develop water vehicles and general purpose machines for the military, and a version of this concept has been put into commercial operation crossing the English Channel. However, as reported by Solomon and Silien,[2]

> "With the exception of water transport, where immersed craft usually experience an extremely high drag coefficient even at low speed, ACVs have shown little application for urban transportation. Since most wheeled vehicles already have a low rolling resistance at urban speeds, there would be little energy savings using an ACV on land."

The disadvantages of the AVC concept such as noise, scattered dust, and difficulty of maneuvering in close quarters would seem to more than offset any possible gain from an application of this concept in a tunneling situation.

Guideway systems can be subdivided into subcategories based on the type of guideway used. The designations selected to identify specific transport modes or a group of modes are:

- Conventional rail - Dual rails with transport modules traveling on top of the rails which also provide guidance for the vehicles.

- Siderail - Transport modules traveling between and supported by rails or other structural members at the sides of the modules.

- Monorail - A single rail with transport modules traveling on top or suspended below the rail which guides the vehicles along the predetermined path.

- Hoist - A transport module traveling vertically or near vertically between guiding elements at the sides of the module which is supported and propelled in a reciprocating manner by a cable.

Other guideway concepts which have been suggested or used for limited, specialized applications include the aerial tramway, a dual rail system with one rail above and the other below the vehicles, and the tracked fluid suspension system.

Aerial tramways originated in the mining industry for the purpose of moving materials over inaccessible terrain. Variations of this method of support and guidance include tramways for passengers ascending mountains or crossing rivers and valleys, and ski chair-lifts. These systems usually support the vehicles on a wire rope cable or a pair of cables. The support cable may also propel the vehicle or a separate cable may be used for propulsion.

The basic principle involves a continuous wire rope riding on pulleys placed at either end of the loop, one of which (the drive pulley) is connected to a power source for moving the rope. A counterweight is connected to an extension of the loop back of the drive pulley to provide tension. Support towers with vertical pulleys mounted on cross-arms are spaced at intervals (usually on high points of the terrain) along the loop to compensate for the catenary effect. Suspension arms (supporting carrier modules) are attached to the rope at intervals.

A top suspension system, such as used with monorails, could be used for supporting the rope loop in a tunnel. To reduce the catenary effect of the ropes, they could be made to ride on rollers in the bottom of an L-shaped trough which would then be supported as mentioned above. This continuous support of the cable or the vehicles would transform the aerial tramway into a hybrid form of monorail system with cable drive.

The special top-bottom dual rail approach, which was built(2) under the names of several of its inventors between 1880 and 1910, appears to have no advantage over the conventional rail concept.

Wheeless, tracked, fluid suspension guideways which are under study for application to rapid transit passenger systems where speed, passenger comfort and quiet operation are of major concern, appear to have little potential for material handling at the relatively low speeds required for a tunnel project. Solomon and Silien[2] have pointed out that major problems to be overcome for successful operation of this concept include compensation for energy wastage needed for lift at low and zero speeds and insignificance of energy saved compared to wheeled vehicles at moderate speeds (50 to 100 miles per hour).

The distinguishing characteristic of a hoist is the reciprocating cable drive. Because of the resulting bi-directional travel along the guideway which can be rails, rods, or wire rope, only one module can be used on a guideway unless a properly located double-guideway passing zone is provided. A single hoist can handle two transport modules with one attached to each end of a continuous cable passing over a drive unit such that one module is raised as the other is lowered. The modules can travel on separate guideways or, conceivably, on a single guideway with a passing zone. If this balanced hoist arrangement is used on an inclined guideway, it becomes a form of Funicular railway as sometimes used to transport people on steep inclines. If a scheme is devised to allow the cable to operate as a unidirectional loop so that more modules can be attached to it, the hoist becomes a form of bucket elevator. If the cable drive is replaced by another drive method such as a rack and pinion as used in a cog railway, the hoist becomes a form of conventional rail or siderail system depending on the location of the guide rails.

Monorail, siderail, and conventional rail systems can be propelled by any one of several drive methods, such as:

- Locomotive Drive - A mobile power unit pulling or pushing one or more transport vehicles. The energy source can be mobile (e.g., a diesel engine) or centralized (e.g., an electric locomotive).

- Self-Propelled - A mobile power unit installed as an integral part of the transport vehicle. The energy source can be mobile or centralized.

- Sidewheel Drive - Stationary drive wheels mounted at the sides of the guideway to bear against the transport vehicles and propel them by the rotation of the drive wheels.

- Cable Drive - A unidirectional loop of cable to which transport vehicles are attached.

- Linear Induction Motor - An electric motor with part of the inductive system mounted on the guideway and part on the transport vehicle, or locomotive, arranged in such a way that the flow of current produces a propulsive force on the vehicles.

The locomotive system concentrates the power sources, and hence weight, in a few units which depend upon traction between the locomotive wheels and guideway rails to propel the train of transport vehicles. The power unit must be sized for the maximum train fully loaded and operating on the maximum grade. For less severe conditions the power capacity is not fully utilized. The limited traction available limits the grade on which locomotive systems can operate. Using electric motors to drive wheels on each car improves the traction and the system becomes a hybrid between locomotive and self-propelled. In some cases the weight concentration requires heavier rail and roadbed support than required for a more uniformly distributed system.

Self-propelled vehicles provide improved traction since there are more drive wheels per unit load and more uniform load distribution. However, the power capability required for steep grades is not fully utilized when operating in horizontal travel and the economy of scale for large power units is lost.

The side-wheel drive improves the traction and power distribution characteristics of the propulsion system by placing a larger number of drive units, using rubber tires for better traction, in acceleration zones, and on inclines where more power is needed. This eliminates unused power capacity if the power units are kept in constant use. For infrequent train operation, locomotive systems or self-propelled vehicles may be more economical.

The cable drive is dependent on traction between the cable and the rotating drive wheel, which moves the cable, to provide propulsion to the transport vehicles. It is, therefore, limited in the number of vehicles it can simultaneously propel up a steep grade. Operating as a balanced system with loaded modules simultaneously descending on the return portion of the cable loop increases the number of modules which can be carried. The component of the cumulative weight of the modules which must be supported by the cable is another limiting factor for this drive method. The cable drive system is similar in principle to a bucket elevator operating on an incline.

The linear induction motor eliminates the dependence on adhesive traction to provide propulsion to the vehicles. This form of motor is derived from the rotating motor by a process of cutting and unrolling both the primary (stator) and secondary (rotor) members and then greatly increasing the length of one of the unrolled members. If the primary member is the one with the increased length and which lies on the ground, the application of poly-phase a-c power to its windings will induce currents in the short-circuited secondary and produce thrust between the two. The thrust will impart a linear motion to the secondary member. With further development the linear induction motor concept may be attractive for application to transport in tunnels since, in addition to the elimination of adhesive traction, there are no wearing parts such as gears or bearings, the motor is noiseless and vibration-free, no air pollutants are produced, and moving parts of the motor are light weight, thus enhancing the ability to accelerate and to climb steep grades. One disadvantage of this concept is the fact that a rather close-tolerance air gap must be maintained between the moving and stationary members of the motor. In the severe environment of a tunnel project this might be a source of maintenance problems.

The "locomotive drive," "sidewheel drive," and "cable drive" designations have been selected to identify specific modes of transport in the conventional rail category. They are defined as follows:

- Locomotive Drive System - A train of open-top cars travelling on a conventional dual rail guideway and propelled by a diesel or electric locomotive.
- Side-Wheel Drive System* - A train of open-top cars travelling on a light-weight, conventional, dual-rail guideway and propelled by stationary, rubber-tired, rotating wheels spaced along the sides of the guideway.
- Cable Drive System - A unidirectional, constantly moving cable loop with open-top cars travelling on conventional rails attached for propulsion up or down a steep grade. The cars are added to and removed from the system at the ends of the cable loop.

Although the siderail support and guidance concept could be developed with any one of the five propulsion methods, the designation "siderail" is used in this study to identify a specific mode** of transport. The major features of this system are the dual-rail (I-beam) support and guidance

*Developed as the SECCAM by Societe Industrielle De Lattre Le Vivier, Le Vivier, France.

**Developed as the Dashaveyor by the Dashaveyor Company, Los Angeles, California.

located at approximately the vertical mid-point of the vehicles, the two electric motors for propulsion mounted on each module, the pneumatic tires and supplementary rack and pinion drive used for improved traction, and the automatically opening and closing covered cars.

The monorail concept for guidance and support of transport vehicles has been proposed and in limited use primarily for demonstration purposes since the early nineteenth century. The lack of apparent economic success of this concept perhaps is explained by the observation of Solomon and Silien(2) that

> "Unfortunately, the facts of structural engineering dictate that (monorail) systems where vehicles are the same size, weight, and carrying capacity would require structures nearly identical in size to those needed for conventional systems."

and/or the comment of Davidson(3) that

> "Assessment of this evidence (that an alternate scheme will accomplish more effectively or economically the functions of support, propulsion, guidance, switching, and lateral stabilization) leads to the conclusion that contemporary monorail schemes are markedly inferior to standard-gauge, dual-rail systems in performance of one or more of the required functions."

However, in the special environment of a tunneling project, where floor space is at a premium, this concept might be considered if it can be assumed that structural support of an elevated monorail suspending transport modules can be provided by the walls or crown of the tunnel. Over rough terrain requiring major modification of the surface to support a continuous roadbed for a conventional rail system, either the monorail or siderail concept, which can have point contact with the surface, perhaps would show some economic advantage for the support system. Any advantage of this nature may be difficult to realize for the more uniform terrain in a tunnel.

Comparison of System Types

Although it is difficult to make generalized statements without the risk of challenge regarding the differences and similarities of continuous and unitized systems, some observations, which seem valid in most cases, can be made if continuous systems are recognized as those in which the transporting vehicle is continuously moving as a closed loop and unitized systems are those in which transporting modules or groups of modules can be controlled independently of each other. These observations, based on the discussion that follows and on the descriptions of the various transport modes in Chapters 3 and 4, are summarized in Table 2-3.

Operational limitations related to the physical characteristics of the muck are summarized for the various transport systems in Table 2-4. This includes the maximum size of the blocks of material to be transported; the result of moisture being present; the effect of stickiness, density, and heat of muck; and the shape of the material.

Further operational limitations on the various systems are found in the first two columns of Table 2-5. These refer to the maximum grade on which the systems are capable of operating including vertical lift applications and the maximum speeds or transport velocities which are considered to be practical for a tunneling application. The operating speeds indicated for the unitized systems in most cases are lower than the maximums of which they are capable. However, they are adequate to sustain the mass flow rates encountered for the range of tunnel diameters and face advance rates considered in this study.

Both the continuous-flow and the unitized transport categories contain systems which are capable of operating in a vertical-lift or steeply inclined attitude as well as a horizontal attitude. This feature can eliminate the need for a material transfer mechanism at the shaft base. Table 2-5 also points out the inherent inability of the continuous-flow types of transport to handle more than one type of material, while the unitized types are capable of transporting bulk materials and other items needed for tunnel construction as well as personnel.

Control systems for continuous-flow transport methods will have to automatically regulate material feed rates at the loading point, the flow in transit, and the flow at the unloading or transfer point. Where a pipeline system is used, the transport velocity and system pressure will have to be monitored and controlled. Automatic interlocking shutoff devices will be required to minimize the damage which might be incurred should there be a rupture in a pipe. All pressure, flow, and safety shutoff devices should be connected to a warning system which, when in operation, would alert maintenance personnel. Pipelines and conveyor belts will require surveillance over the system for its entire length.

Where feasible, the unitized transport traffic should be automatically operated and monitored to a predetermined schedule in order to minimize the hazards of manual operation of a complex traffic system. If a transport unit fails, the control system must isolate the failed unit and, if possible, automatically route all other traffic around it or remove the unit from the system. If the failure involves a guideway or roadbed, it

TABLE 2-3

COMPARISON OF TRANSPORT SYSTEM TYPES

Item	Continuous	Unitized
Carrier media	Closed loop	Modular
Media flow	Continuous	Intermittent or continuous
Guideway	Continuous loop	Dead end or loop
Load and unload	Continuous	Intermittent or continuous
Power unit capacity	Single unit requires maximum capacity at initial installation; may use series or booster units.	Units added as needed; size depends on module size.
Material carried	Only bulk materials	All materials
Payload	Single material; continuous, unidirectional flow.	Multiple materials; modular, bi-directional flow.
Flow variation	Difficult to accommodate unless capacity in excess of normal requirement is available in system.	Can accommodate by varying number of modules in system.
Guideway failure	Complete system shutdown	Can be bypassed in many cases
Carrier failure	Complete system shutdown	Module removed from system
Lift capability	Fluid media - vertical Belt media - limited	Traction drive limits angle of slope
System extension	Hydraulic - difficult	Less difficult
Tunnel cross section	Minimum required. Depends on media flow rate.	Depends on module spacing and speed.

TABLE 2-3 (continued)

Item	Continuous	Unitized
Structural support	Can support from wall and crown. No roadbed.	Wall and crown support feasibility depends on module size. Some modes may require prepared roadbed.
Automatic control	Less complex	More complex due to cyclic operation.

must be located and traffic must be stopped or routed around it. System surveillance may be performed by electronic means, by patrol, or by a combination of both, depending on the specific requirements.

System unloading will involve the use of transfer mechanisms at the base of the shaft unless the transport system is of the type that can operate horizontally as well as on a steep incline, or as a vertical lift system. As shown in Table 2-5, the hydraulic and pneumatic pipelines in the continuous flow category are capable of vertical lift transport. Some types of conveyors (including the closed or zipper conveyor, the serpentine conveyor and the bucket elevator) are used as vertical lift transport mechanisms for relatively short distances and low tonnages. Belt conveyors are generally restricted to a maximum slope of 51 percent (about 27 degrees), depending upon the angle of repose of the transported bulk material. If used in a tunnel where access to the surface is through a vertical shaft, a belt conveyor would discharge its material into a transfer mechanism for transport up the shaft by another mode.

At the present time, there are several types of commercially available unitized transport systems with vertical or steep incline capability which can perform both horizontally and for vertical lift. The siderail type of system accomplishes the vertical lift by means of a rack and pinion drive. Another unitized system which can operate vertically is the hoist, which is designed primarily for that application and is not normally adaptable to horizontal operation. The remainder of the unitized systems are confined to operation on slopes of 45 degrees (100 percent grade) or less. The side-wheel drive, conventional rail system is claimed to be able to negotiate 100 percent grades. Various types of power assistance mechanisms can be applied to unitized transport systems in both upgrade and downgrade situations. These include a cable tow and an electrical booster which, when applied to a system, have proven to be effective in increasing the system's capability to operate on steeper than normal grades.

TABLE 2-4

MUCK PROPERTIES RELATED TO TRANSPORT SYSTEMS

	Mode of Transport \ Physical Characteristics of Muck	Block Size	Moisture	Stickiness	Density(c)	Heat and Miscellaneous Factors	Shape(d)
Continuous	Conveyors	To one-fourth belt width.	Will drain off in transit.	Will load belt excessively.(b)	Tonnage increases with higher density.	May require special belts. 200°F+. Incompatible.	All.
Continuous	Hydraulic	Need 50% < 0.002 inch. May be large block limits.	Presence favors system.	Implies moisture OK.	High density increases tonnage and critical velocity.	Probably OK. Steam may be generated.	Flaky materials favored.
Continuous	Pneumatic	Works better with small material size.	Dry material better. Some moisture OK.	Cannot handle sticky material.(b)	High density increases tonnage and critical velocity.	May require insulation.	Flaky materials favored.
Unitized	Conventional Rail	All.	High content may affect rail ballast.	OK, but may require shaker for unloading.	Tonnage increases with density.	May require insulation.	All.
Unitized	Siderail	Limited by module size; 6 inches OK.(a)	Will drain in inverted position. Special electrical features required.	Difficult to unload.	Tonnage increases with density.	May require insulation.	All.
Unitized	Monorail	Limited by module size; 6 inches OK.(a)	Will drain off in transit.	Difficult to unload.	Tonnage increases with density.	May require insulation.	All.
Unitized	Hoist	All.	Will drain off in transit.	May require special unloading feature.	Tonnage increases with density.	May require insulation.	All.
Unitized	Free Vehicle	All.	High content will affect road requirements.	May require special unloading feature.	Tonnage increases with density.	May require insulation.	All.

(a) Blocks in excess of 6 inches may require crushing.
(b) Sticky materials incompatible with conveyors and pneumatic systems.
(c) Density not a critical factor due to low percentage of very light or very heavy rock.
(d) Muck shape a minor factor.

TABLE 2-5

CAPABILITIES OF TRANSPORT SYSTEMS

	Operational Capability / Mode of Transport	Maximum Grade Including Vertical Lift	Maximum Transport Speed	Materials Handled					
				For Transport System Extension	Wet or Dry Bulk	Steel Supports and Liners	Personnel and Small Miscellaneous Packages	Lumber, Beams, and Rock Bolts	Large Construction Equipment
Continuous	Conveyors	51%[a]	To 20 fps (1200 fpm)	No	Wet - No Dry - Yes	No	No	No	No
Continuous	Hydraulic	Vertical	To 15 fps	No	Wet - Slurry (Preferable)	No	No	No	No
Continuous	Pneumatic	Vertical	To 100 fps	No	Wet - No Dry - Yes	No	No	No	No
Unitized	Conventional Rail	5%[c] 100%	To 59 fps[b] (40 mph)	Yes	Wet - In Containers Dry - Yes	Yes	Yes	Yes	Yes
Unitized	Siderail	Vertical	To 73 fps[b] (50 mph)	Yes, in small quantities	Yes, in small quantities	Yes, in small increments	Yes	Yes, size limited	No
Unitized	Monorail	100%	To 73 fps[b] (50 mph)	Yes, in small quantities	Yes, in small quantities	Yes	Yes	Yes, size limited	No
Unitized	Hoist	Vertical[d]	To 60 fps[b] (3600 fpm)	Yes	Yes	Yes	Yes	Yes	Yes, in increments
Unitized	Free Vehicle	14%	To 51 fps[b] (35 mph)	Yes	Wet - In Containers Dry - Yes	Yes	Yes	Yes	Yes

(a) Troughed belt conveyors. Other types such as zipper conveyors and bucket elevators used in vertical lift applications of relatively limited capacities and distances.

(b) Assumed speed limitation for operation in tunnel; 40 mph may exceed cable drive capability.

(c) Locomotive, 5%; sidewheel and cable drive approach, 100%.

(d) Hoist not adaptable to horizontal operational attitude.

The mass flow requirements for the transport system vary with the cross-sectional area of the tunnel and the advance rate of excavation. This applies both to the transport of muck from the working face and the inflow of tunnel support materials, and personnel. Mass flow requirements for muck range from 95 tons per hour for an advance rate of 300 feet per day in a 10-foot tunnel to 7,645 tons per day for an advance rate of 1,500 feet per day in a 40-foot tunnel. The inflow of construction and tunnel support materials can be equivalent to as much as 30 percent of the outflow of muck in tons per hour. This percentage can vary considerably, since it is dependent upon the type of tunnel supports required, and the type of transport system being used. For example, conventional rail and free vehicle systems might require some kind of roadbed on which to operate and the material required for this bed could represent a large portion of the incoming materials. Ground support materials can vary from none for highly competent rock to several tons per foot of advance if full circle support is required.

Table 2-5 summarizes the general types of materials which can be handled by the various types of continuous flow and unitized transport systems. This chart was developed for normal tunneling operations and may not include all special cases.

Extending a transport system of either basic type while maintaining continuous loading capability results in serious interface problems. These are apparent to a greater degree in the continuous-flow transport group than in the unitized transport group. This is due to the fact that the vehicle in a continuous-flow system must be in operation without interruption to be effective. A broken conveyor belt must often be unloaded, at least partially, to repair it or splice in a new section. Stoppage in the flow of a fluid system allows the payload material to settle and resuspension may be difficult. On the other hand, the unitized systems are cyclic in operation and conceivably could withstand a disruption in the loading schedule. Fluctuations in loading rates could be compensated by adjusting transit speeds and the number of carrier units used.

Up to the present time, experience is lacking in the technique of extending a transport system of either basic type while maintaining uninterrupted operation of the system, particularly when the point of system extension is in the loading zone as must be the case for a tunneling project. Although conveyors and conventional rail systems have been extended in tunneling operations, the extension tasks were accomplished at times when the excavation equipment was not operating. There is no evidence of either a hydraulic or pneumatic pipeline system being advanced while in operation, as they are usually utilized for a fixed point-to-point type of transport. A sliding floor which permits loading to continue during system advance has been used in some cases. However, there is little available evidence to indicate that this scheme has been used to keep pace with the excavation equipment on a continuous basis rather than to advance sequentially with excavating and mucking equipment as is the more common practice. It is apparent that there is a definite requirement for technological advances in the field of transport system extension methods which would be compatible with the projected tunnel advance rates.

In a continuous-flow transport system, all elements of the system must function during the full time of system operation. If any one of the system components fails, the entire system will have to be shut down. It is conceivable that during a 4-month operational period, a failure could occur which would require replacement of one or more of the system components. Therefore, in order to minimize the time lost by system shutdowns due to failure of components, it might be well to assume that inventories of spare parts contain a sufficient quantity to rebuild 5 percent of the linear length of the completed system. These spares would be in addition to the components required for normal system extension.

Unitized systems present a different problem in that the failure of a system component would not necessarily mean a complete system shutdown. In the event of a guideway failure on a double-track conventional rail system, the break could be isolated through use of cross-over switches and the traffic rerouted around it. When repairs are completed, the traffic would return to its normal pattern. Should a load carrier unit fail, it could be routed out of the traffic pattern and replaced by another unit. Although, in principle, the same emergency measures could be taken for the siderail and monorail systems; in practice, bypassing a guideway failure in these systems may be more difficult than for the conventional rail systems due to the more complex structures used for the guideway. In any case, a guideway failure requiring bypassing would tend to diminish the capacity of the system since a portion of the guideway would need to be used for two-directional traffic. The closer together the trains or modules were operating on the guideway, the greater would be the effect on the system capacity.

Failure of the drive cable or the guideway in a cable drive or hoist system would cause a complete shutdown since the vehicles can travel only on the path of the cable and cannot be switched from one leg to another of the guideway.

Spare parts inventories for unitized guideway systems should include at least one drive unit replacement and 5 percent of the required total of load-carrying modules. For free vehicles, the inventory should include an extra 25 percent of spare vehicles as well as additional vehicle components. Free-vehicle failure would mean immediate replacement of a unit with repairs being accomplished in the maintenance area. The design of any of these transport systems should include provisions for modular replacement of components and subsystems for both scheduled and unscheduled maintenance.

In general, the continuous-flow transport systems occupy less tunnel cross-sectional area than the unitized systems because the payload material is more uniformly distributed over the length of the tunnel. They can be installed on the sidewall of a tunnel, thus releasing floor area for the unitized systems which are required to transport the construction materials which cannot be handled by the continuous systems.

Figures 2-2a, 2-2b, 2-2c, and 2-2d show a comparison of the cross-sectional areas occupied by the two types of systems in tunnels ranging from 10 to 40 feet in diameter. Circular tunnels were selected for illustration because more of their cross-sectional area would have to be sacrificed for roadbed usage than that of horseshoe or vertical-walled tunnels.

AUXILIARY EQUIPMENT

The auxiliary equipment required to supplement the transport modes in a complete transport system is determined by the transport modes selected and, in some cases, by the method of excavation used. In making comparison of alternate transport modes, any auxiliary equipment required for satisfactory operation of a particular mode should be considered as part of that mode in order to obtain a valid comparison of modes.

The auxiliary equipment can, in general, be categorized by function as loaders, transfer equipment, unloaders, and processors.

Loaders

Loaders for Conventional Excavation - Where conventional excavation is used and the muck is produced by drilling and blasting, the loader must be more rugged and adaptable to handling blocky and abrasive material. In smaller tunnels up to 10 or 20 feet, the overshot loader is used almost exclusively. The overshot loader, which can be either air or diesel-operated, is a very compact unit and is either rail or crawler track mounted. It loads by crowding the bucket into the muck pile, shoveling it up, and throwing it back over the rear of the machine. It is designed to swing in a radius of approximately 120 degrees and is extremely maneuverable and fast loading. The material thrown over the back of the unit is generally loaded either onto a conveyor belt or into a transfer unit, which could be a belt or a scraper, and then into rail or rubber-tired cars. For side-loading, diesel mucking machines may be equipped with a side dump "LIBU" bucket.

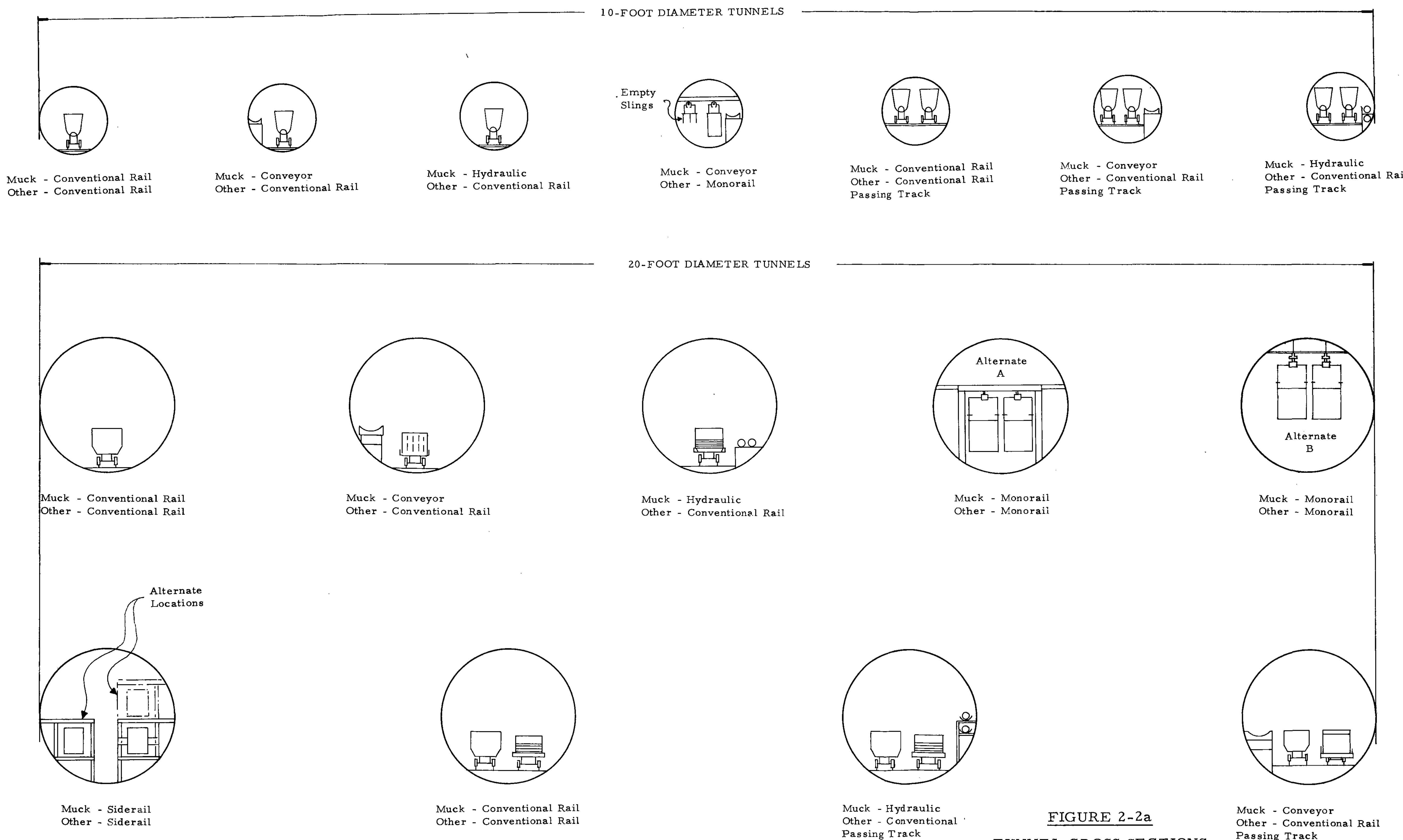


FIGURE 2-2a

TUNNEL CROSS SECTIONS
(10 to 20 Feet Diameter)

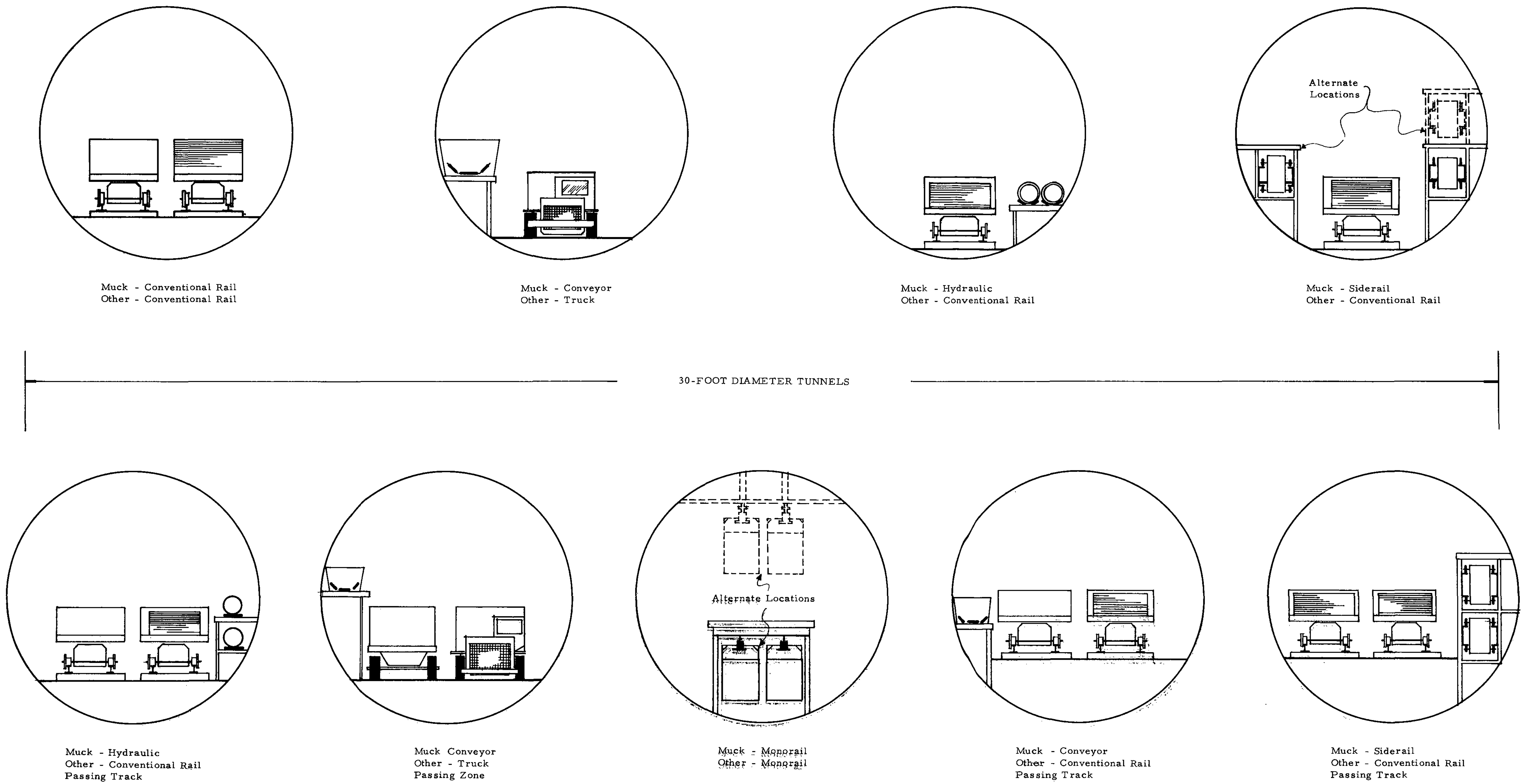


FIGURE 2-2b

TUNNEL CROSS SECTIONS
(30 Feet Diameter)

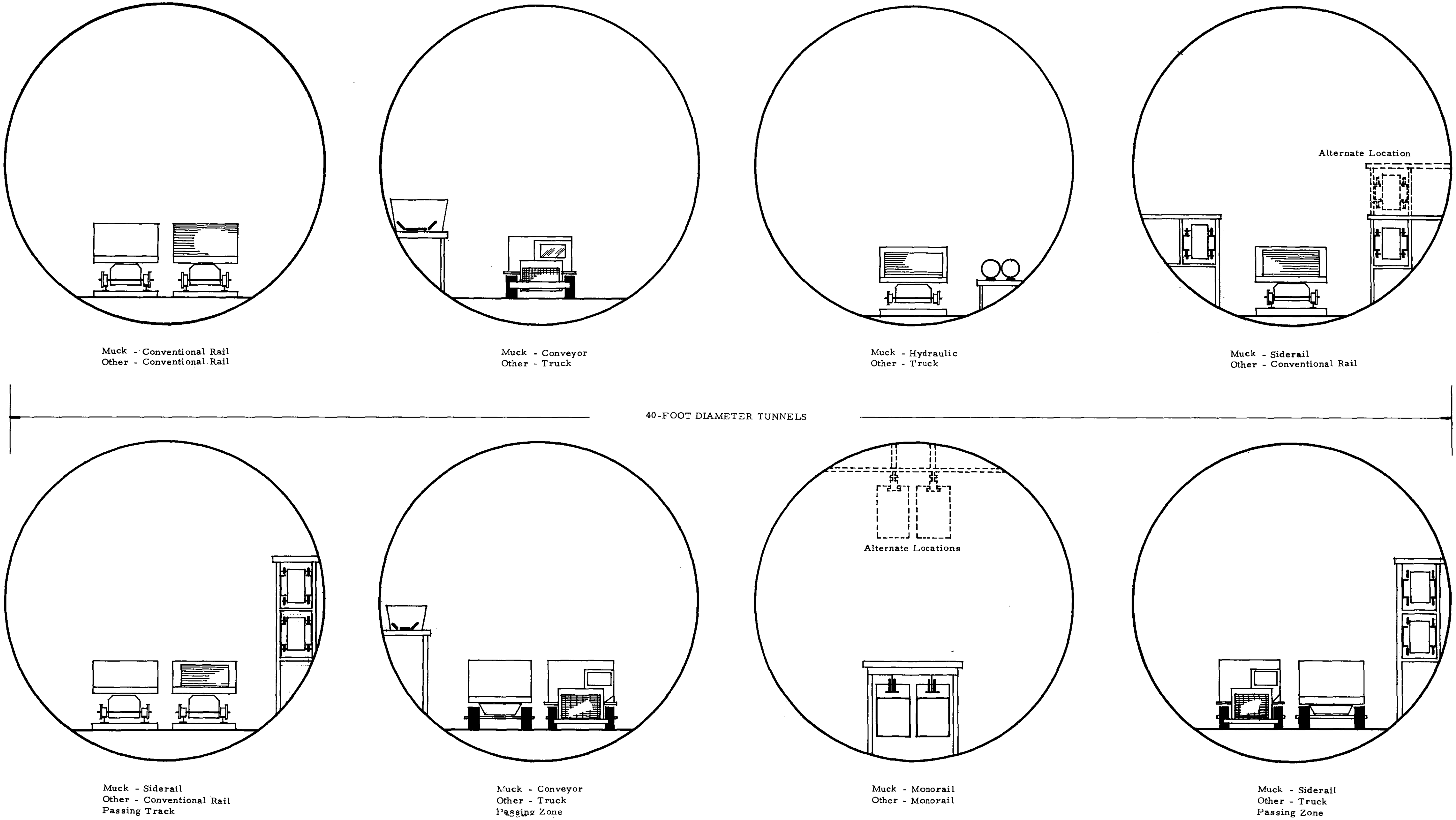
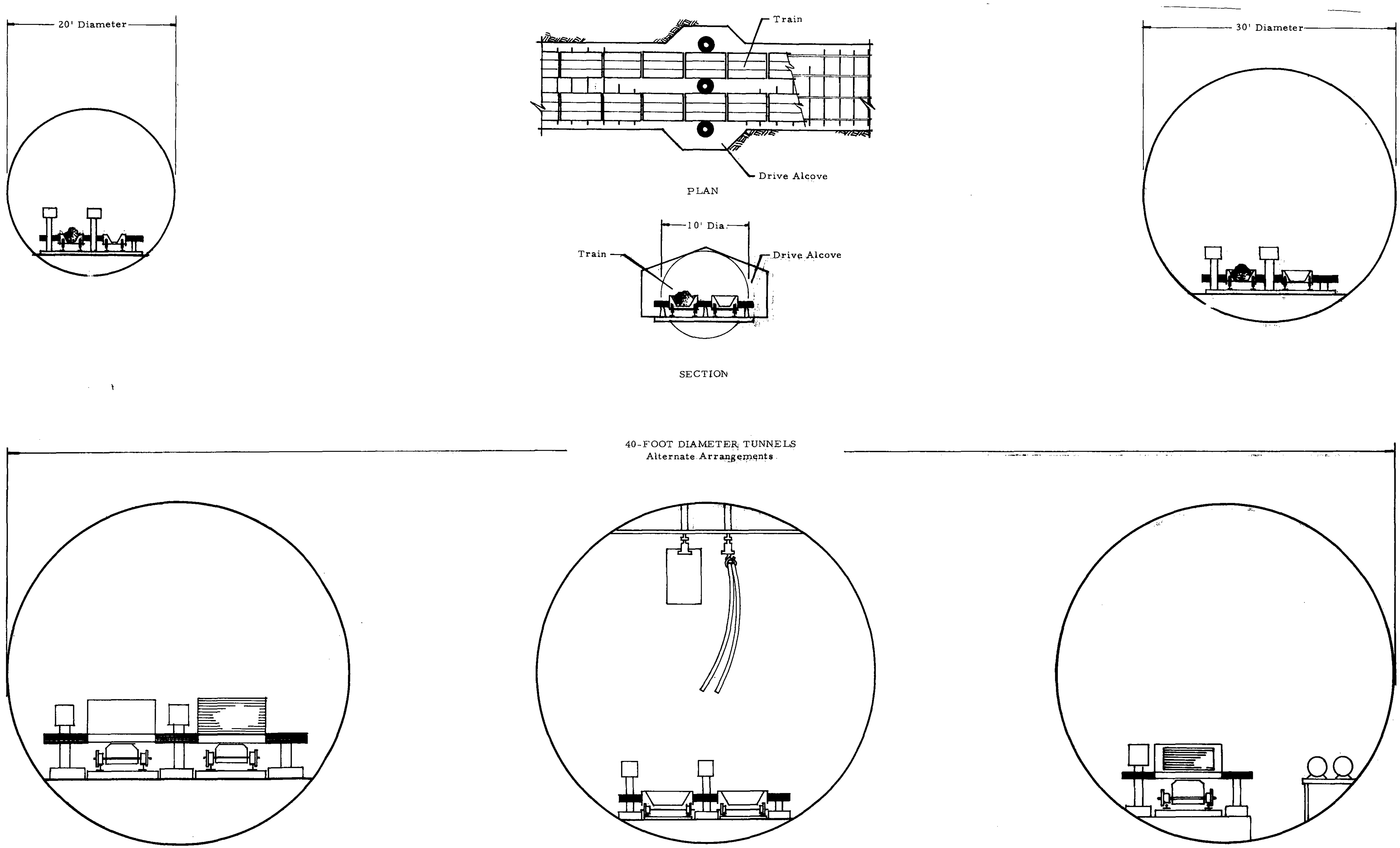


FIGURE 2-2c

TUNNEL CROSS SECTIONS
(40 Feet Diameter)



Muck - Side-Wheel Drive
Other - Side-Wheel Drive

Muck - Side-Wheel Drive
Other - Monorail

Muck - Hydraulic
Other - Side-Wheel Drive

FIGURE 2-2d

TUNNEL CROSS SECTIONS - SIDE WHEEL

A unit slightly larger in capacity is the Conway electrically operated mucker which is equipped with a tilting dipper. The unit crowds into the muck pile in a manner similar to the overshot loader, but by making use of a tilting bucket which pivots on the forward crowding boom, it dumps its load back onto a pan which in turn feeds onto a conveyor belt. The belt then carries material back, up, and over the Conway mucker either into cars or onto a conveyor belt.

For the larger tunnels and especially ones of shorter length, the unit which is gaining much favor is the transloader, or dumpster type. This unit is usually rubber-tire mounted and crowds its way into the muck pile similar to both the overshot loader and the Conway mucker; it differs in the way it dumps its large bucket into a container immediately behind the crowding bucket. The unit normally fills its bucket within two or three scoops and then has the capability of backing up, turning, and running at a fairly high rate down the tunnel to deposit onto some other conveyance; or, in many cases, it simply dumps its load into a pocket previously constructed on the side of the tunnel until the round has been mucked out. Operating in this manner, it is capable of clearing the face very rapidly, allowing for drilling and blasting of the next round to continue while the transloaders either pick up material and carry it out of the tunnel or load it onto some other primary conveyance system.

Another type of loader which has undergone considerable development is the scraper or grab-type loader. This unit has been used more in the European tunnels and on excavations in foreign countries than in the United States. A similar unit is built by Wemco* in the United States. It operates by scraping the material back from the face onto a conveyor belt or pan feeder by means of grab arms which are usually hydraulically powered. A "duckbill" loader made by Joy** is often used in loading slabby material such as shale or coal. This is an electric loader with an apron which is crowded into the muck pile. Two arms, by alternate movements, rake the muck up the apron onto a conveyor belt. Some units have slusher type buckets mounted on a forward boom which brings the scraper forward, drops it into place; and then either by cable or hydraulic arms, scrapes the muck back onto the feeder. In very large tunnels or underground excavations, the conventional swing type shovel is used. This unit is adaptable only to large excavations and does not have the speed of operation of the other type loaders. However, where reliability is important and the speed of loading is secondary, this unit has its application.

*Wemco Division of Envirotech Corporation, Salt Lake City, Utah.
**Joy Manufacturing Company, Pittsburgh, Pennsylvania.

Loaders for Mechanical Boring Machines and Continuous Miners - The loading equipment used with mechanical type boring machines is usually designed as an integral part of the boring machine. Generally, it falls into one of three categories. The most commonly used is the rotary bucket elevator which is attached to the boring head and rotates with the bits. These elevator buckets are rigidly attached to the head and scrape up the material from the bottom and sides of the tunnel as the head rotates, carrying it to the top where they are inverted and deposit their load onto a conveyor or other type of transfer feeder.

A second type of bucket elevator is the chain-bucket type which is normally used on continuous miners in the coal industry. These units have the capability of cleaning a flat surface on the bottom of the tunnel as it is required for the bottom of a horseshoe tunnel. The buckets move from side to side against the heading, and carry the material to the top side of the boring machine by a chain driven on a sprocket and gear arrangement. They then are inverted and dump their material onto a transfer conveyor or a transfer feeder.

The third type of loader used with the mechanical moles has been developed in the European countries where the multiple head boring machine is used. This unit usually consists of several rotary heads driven by independent motors. The entire configuration is normally mounted on a central shaft and is rotated at a slower rate than the cutter heads in such a manner as to cover the entire face desired for excavation. With this type of unit, a scraper or hoe-type loader is sometimes applied. This unit consists of hydraulically operated scrapers or hoes which pull the muck back from the face and deposit it onto a conveyor or a transfer feeder. With some designs the rotary elevator bucket is also used.

Loaders for Hydraulic Transport - In most cases, loaders for hydraulic transport will not differ appreciably from those for conveyor loading or other types of conveyance, as the prime requirement is to get the muck back from the face and put it onto some transfer mechanism. In a hydraulic transport application, all of the previously described loaders could be used to carry the material back to a hopper or sump, where the water will be mixed with it.

As there have been only one or two recorded tunnels in which hydraulic transport was tried, there has been very little development done in this area. From this, it appears that this type of transport for closed-circuit operation will borrow techniques used at two separate mines (one in Michigan and one in France) as well as from numerous other types of open-circuit loading systems which have proved satisfactory in various metallurgical mills. The closed-circuit systems, which conserve the power of the hydrostatic head, consist of screw-type conveyors which inject the solid material into the water line. Another type makes use of a lock and tank system, feeding the material into the line under hydrostatic pressure. Another system as yet untried employs the use of an eductor coupled with a suction pump, which also injects the muck into the line under hydrostatic pressure. None of this equipment has been developed for tunnel use, but it should find applicability when hydraulic transport is fully developed for tunnel operation.

Transfer Equipment

Transfer equipment consists primarily of conveyors, transfer pan feeders, or apron feeders. Also, scrapers, slushers, and bins with automatic or manually operated valves are used.

Conveyors generally consist of two major types. One type is the extensible telescoping conveyor which normally consists of a set of conveyors stacked vertically and mounted on the back end of the mole, or on a structural rack or gantry which can be towed behind the loading equipment. The top conveyor normally is loaded first; and then by cascade action, each successive conveyor is loaded as it is extended. This arrangement allows forward movement of the gantry conveyor unit as it follows the advance of the heading while continuing to load onto a primary transport system, such as railroad cars or conveyor. Another conveyor type of transfer mechanism is the tripper conveyor unit, which is not used extensively underground but should be very adaptable. This unit consists of a movable head pulley and chute arrangement which is capable of traversing the full length of the conveyor belt; and by discharging into the chutes, it is capable of loading other belts or cars on either or both sides of the conveyor.

Pan feeders are normally divided into two groups: the electrically-driven, vibrating type and the mechanically eccentric driven unit. Both of these operate on the principle of propelling the material forward due to the eccentric vibration of the pan. They are especially adaptable for use with dry material without too many large boulders. For use with heavy, coarse boulders, the apron feeder becomes the most usable piece of equipment. This consists of very heavy steel plates driven over chain sprockets, the flat plates being linked together with pins similar to that of the tread of a crawler-tractor. Both pan feeders and apron feeders are equipped with sideboards and are capable of carrying the material in either direction. Belt feeders are used for smaller sized material.

Bins and chutes are quite typical of transfer equipment, especially at the base of shafts or junction points in the tunnel. The bins provide surge capacity and permit material to be passed in several directions by the use of automatic or manually operated chutes. Bins may be used strictly for surge, or they may be used as measuring pockets to measure the proper quantity of material for skips or other transport modules.

Unloaders

Unloaders can be classified into two major types; those which are installed on units such as railroad cars, trucks, or Athey cars and move with the units as an integral part of their assembly; or those which are installed at one location, usually over a pocket or some other feeding arrangement.

Unloaders which are an integral part of the transport modules may be either a scraper scraping the material from the car by opening an end, or they may be air-operated hoppers installed on the bottom of the cars or on side dump cars with the air or hydraulic operation as part of the integral design of the car. These unloaders are most often used when dumping must be done at several locations.

Fixed installation unloaders may be the camel-back side dump arrangement, which is capable of tipping the cars as they are pulled through the unloading station; or the rotary dump which turns over one or more cars in a train. These are used with or without rotary couplings installed on the train. If equipped with rotary couplings, the cars can be turned over and dumped without decoupling.

Processors (Crushers, Screens)

Underground processing of the muck has had only limited application and that has been almost completely confined to mines. It is becoming increasingly popular in mines, especially coarse crushing of ore before hoisting, as it has been shown that substantial savings can be made on maintenance and capital costs. By eliminating the loading and handling of large chunks of material, wear on liner plates and equipment is considerably reduced; and as the ore must eventually be crushed at the mill, large capital cost savings can be made since lighter weight, cheaper transfer equipment can be used. This is not the case, however, for tunnels because the material is usually wasted or used for some purpose where crushing is not required. Reduced equipment maintenance might in some cases make crushing worthwhile, but of greater interest is the use of crushing to make transport by conveyor, hydraulic, or pneumatic systems feasible for material which otherwise would require a unitized mode of transport.

Some major companies are experimenting with low-head compact crushers. Eimco,* for example, is building a horizontal jaw crusher with a unique horizontal eccentric feed arrangement especially suitable for use in a tunnel, and Smith Engineering** has recently announced a new low profile crushing unit. The horizontal jaw crusher is essentially the same as the vertical unit lying on its side. The swing jaw is actuated by an eccentric or toggle imparting a squeezing or crushing action to the jaws.

Short head cones or a disc crusher, when equipped with horizontal feeder, require only minimum head room and are feasible for use in the larger tunnels. These crushers break and fragment the rock, which is fed into the top of the unit, by squeezing the material between two conical surfaces. The action or power is imparted through an eccentric which turns about a vertical shaft attached to the mandrel or inner conical surface. The outer conical surface, known as the "shell," is stationary and the material is crushed between them. The disc crusher operates in a similar manner; the main difference being in the flatter angle of the cone.

Space requirements for contemporary portable crushing equipment vary with the type of crusher, its capacity, and the manufacturer. A trailer-mounted vertical jaw crusher of about 1,000 tons-per-hour capacity would have a dimensional envelope of about 40 feet long by 20 feet high (including feeder) by 14 feet wide. This would be fairly typical of the units produced by Eimco Corporation, Smith Engineering Works, and Joy Manufacturing Company.*** Low profile units require less headroom but may have greater overall length than the vertical type.

The two types of cone crushers, standard and short head, have about the same space requirements for a given capacity. A trailer-mounted unit with a capacity in the 1,000 ton-per-hour range would require a slightly shorter length carrier and would need a little less head room than a vertical jaw crusher unit. The widths of the assemblies would be about the same.

For hydraulic pumping where a large percentage of fines in the material is required to accomplish economical operation, crushing most likely will be required and the size gradation of the material could be controlled through screening and recirculation as done in mills. This will require special attention as failure of hydraulic pumping systems installed in the past was attributable to lack of sufficient fines and poor control of the slurry mixture.

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*Eimco Corporation, a Division of Envirotech Corporation, Salt Lake City, Utah.

**Smith Engineering Works, Milwaukee, Wisconsin.

***Joy Manufacturing Company, Pittsburgh, Pennsylvania.

Space requirements for vibrating screens depend largely on capacity and arrangement. Screens can be sloped at various angles (generally 15 to 20 degrees) and can be composed of one or more decks. A nominal 6-foot by 16-foot triple-decked screen would require an area about 16 feet by 10 feet by 13 feet in height. A single decked screen with the same slope would need the same floor area, but about 2 or 3 feet less head room. For the purpose of controlling size gradation and density, the heavy-duty vibrating screens coupled with sumps and metering valves of the most rugged design will be required in a tunneling operation.

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CHAPTER 3

CONTINUOUS FLOW SYSTEMS

A continuous flow transport system characteristically provides the capability of an uninterrupted flow of materials for the entire length of the system, from the point of loading or feeding to the point of discharge. The capital investment for such a system employed in a horizontal straight run has a direct relationship to the linear length. In tunneling work the continuous-flow systems would normally be designed to transport the muck only and must be supplemented with a unitized transport system to handle the inbound flow of construction tools and materials, fabricated items, and transportation of personnel.

CONVEYOR SYSTEMS

A conveyor system for transporting bulk materials includes several basic components. A drive unit, usually consisting of a motor and a speed reducer, provides the motive power. The transport medium can be a continuous belt with or without cable reinforcement supported on idlers; a continuous series of metal pans on flights supported on chains; or a continuous belt which completely encloses the transported material and is supported on rollers. Drive speeds and dimensions of the components can vary to give a wide range of capacities. There are other types of conveyors for specific uses in which the transport media may be a series of metal rollers or a continuous chain with load-carrying attachments.

The types and basic components of conveyor systems are normally designed and selected for a particular application, based on the physical and chemical characteristics of the material to be handled; capacity and rate of travel; criticality and duration of continuous operation; feed and discharge conditions; space and grade limitations; and site environment and safety requirements.

Belt Conveyors

The troughed-belt conveyor is most commonly employed to transport bulk earth materials, particularly on level grade or inclines up to 51 percent. While flat-belt and zipper-type conveyors have been utilized in special applications of this nature, they can be looked upon as derivations of the troughed-belt type. For personnel transport, a flat-belt conveyor which becomes a moving walkway is normally used. A flat-belt conveyor is also used for moving packaged or lightweight, fabricated materials as well as some types of bulk materials. In this latter application, the angle of repose of the material would have to be sufficient to minimize spillage. In addition, the flat-belt conveyors are used for bulk materials where it is necessary to plow off some of the material at intermediate points along the conveyor run.

Belt conveyors which can completely encase the transported material are used where relatively short vertical lifts are necessary, such as from floor to floor in an industrial plant. These are known as zipper conveyors due to the interlocking teeth on the edges which engage after loading and form an envelope around the material.

Bucket elevators, which may be composed of a series of load-carrying modules or buckets attached to a continuous belt (or, in some instances, attached to parallel continuous chains) are generally used for short lifts of bulk materials in industrial applications. If the zipper conveyor or the bucket elevator were to be utilized for a vertical lift application, such as moving muck from a tunnel to the surface, the weight of material in the system must be considered. Assuming a shaft depth of 500 feet and a material flow rate of 5,000 tons per hour, the weight of the muck alone would impose a load of about 83 tons on the equipment support point at the top of the shaft. However, if the shaft were 3,500 feet deep, the load on the head-wheel would be about 580 tons with a similar material flow rate.

Because troughed-belt conveyors seem to be more suitable than other conveyor types to muck transport, they are selected to represent the conveyor mode of transport for comparison with other continuous and unitized modes of transport. Troughed belts are characterized by their configuration in which the belt forms a continuous, longitudinal trough, facilitating the transport of bulk materials at high belt speeds. The depth of the trough and the angle of the belt sides are determined by the angle of the troughing idlers on which the belt rides. These range from 20 to 45 degrees. The major factors which govern the capacities of trough-belt conveyors are belt speed, belt width, troughing angle, and the density and angle of repose of the material handled.

Since the load is distributed over the entire transport distance, troughed-belt conveyors have minimum point loading, thus requiring minimum structural support and also requiring minimum cross-sectional area for a given travel speed. They can be located in most all areas of the tunnel. When supported from the tunnel walls as shown in Figure 2-2, valuable floor area is released for other purposes. Figure 3-1 relates the width of the belt to the cross-sectional area of the conveyor with and without a supporting structure. The maximum heights and widths of the conveyor structure are also shown in Figure 3-1 for various belt widths.

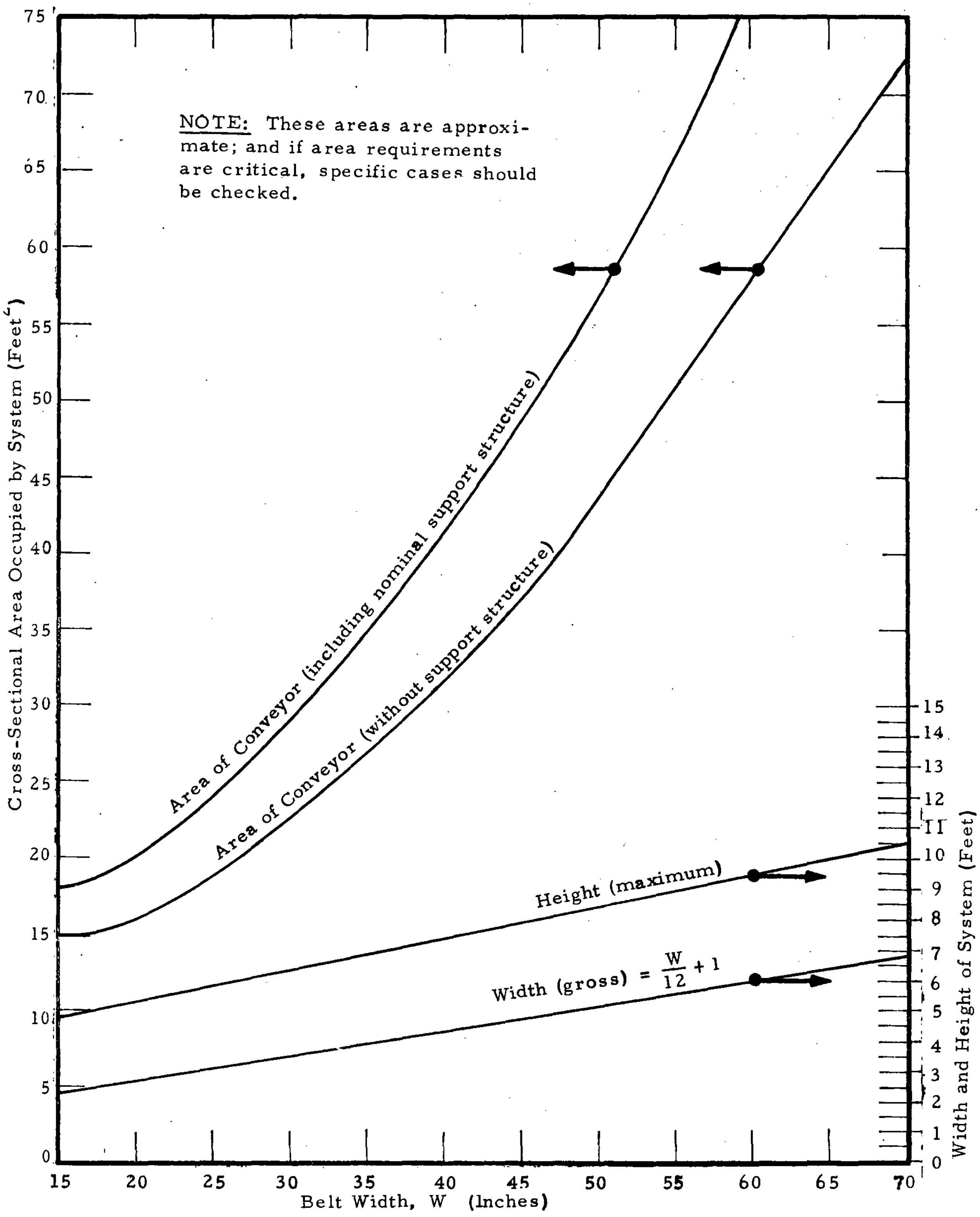


FIGURE 3-1

CONVEYOR BELT WIDTH AND CROSS-SECTIONAL AREA

At the present time, troughed-belt conveyors are capable of transporting bulk material at flow rates commensurate with the projected tunnel advance rates. This can be accomplished both on the horizontal and on inclines up to 51 percent. This capability is reflected in the fact that with an inclined shaft the only transfer of materials would occur between the horizontal and the inclined conveyors, which might be eliminated by using a suitable radius of curvature and combining the two into one continuous belt. While most belt and conveyor component manufacturers recommend belt speeds in the 550- to 700-feet-per-minute range (approximately 8 miles per hour), belt conveyors have been operated successfully at speeds of 1,000 to 1,100 feet per minute (12 miles per hour). At these high speeds, narrower belts can be used to attain the same capacities as wider belts at slower speeds. Figure 3-2 shows the relationship of the mass flow rate to the conveyor belt width at standard speeds recommended by manufacturers and at speeds in excess of these which have been found satisfactory in use.

Where vertical shafts are the only means of access to the horizontal section of the tunnel, a surge bin or hopper would be used to receive the muck from the discharge conveyor and transfer it by a suitable feed device to the vertical mode of transport.

Extension Methods - There are several methods which could be employed to extend or advance a belt conveyor at a pace compatible with the tunnel advance. Three of these are illustrated in Figure 3-3. As the tunnel is extended, additional lengths of conveyor could be assembled, or inserted as a preassembled unit, at the tunnel face or tail pulley end of a stationary conveyor line.

Advancing the stationary transport conveyor from the tail pulley end behind the excavator would entail the use of a mobile feeder conveyor attached to, and moving with, the excavator. The feeder mechanism would consist of one- or two-belt conveyors mounted on structural framework. This framework would straddle the stationary conveyor and move along on wheels with the excavator. The feeder conveyor(s) would take the muck from the excavator and feed it onto the transport conveyor belt through a transfer chute. The feeder conveyor could also be offset from and feed the conveyor through a cross-feed conveyor or chute. In either case, the mobile feeder conveyor would be of sufficient length to allow working space and time for installation of additional segments to advance the transport conveyor.

The stationary conveyor could be a single, long conveyor with frame and idler units being added as the feeder progressed along the tunnel. However, before each new section of conveyor could become operable, the system would have to be stopped to permit the splicing of an additional length of belt onto the existing one to accommodate the added section.

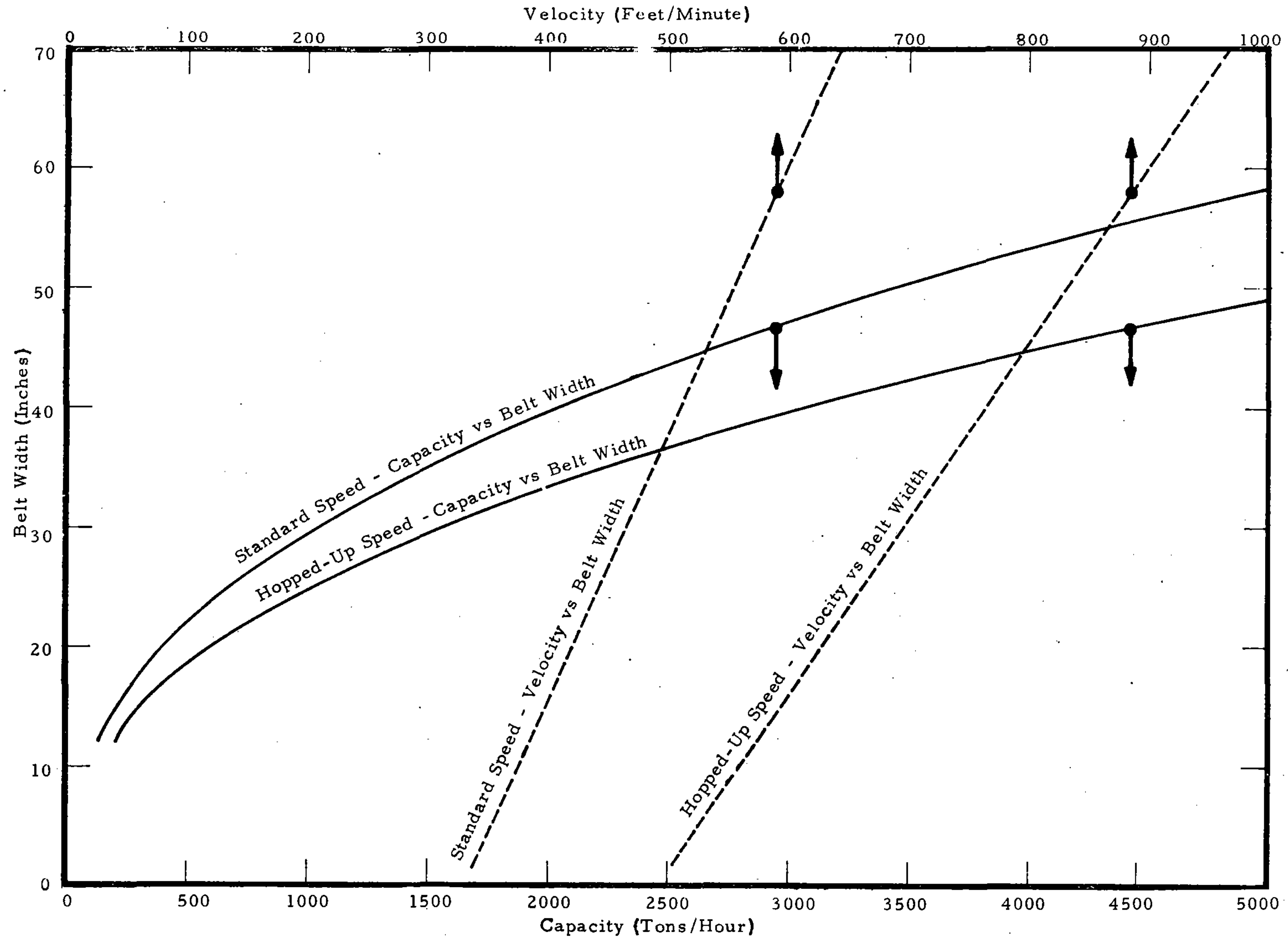
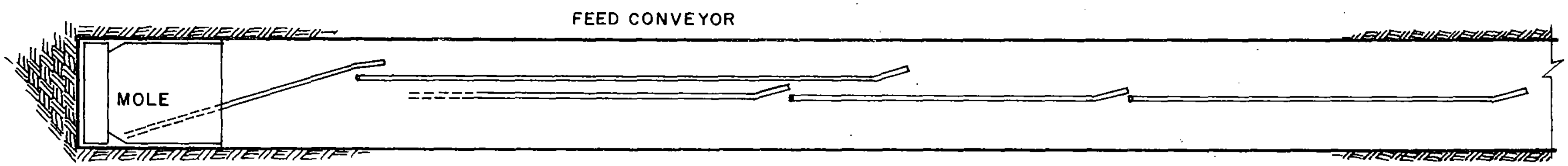
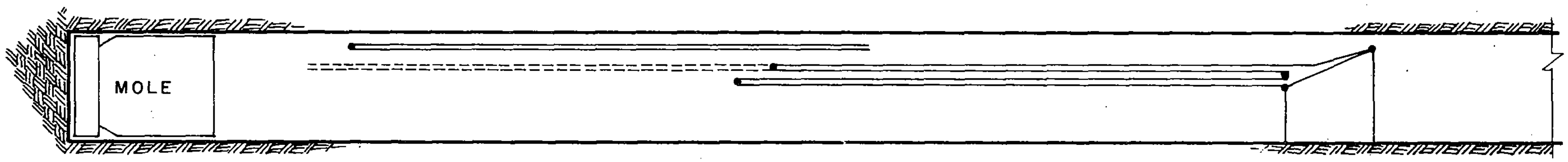


FIGURE 3-2

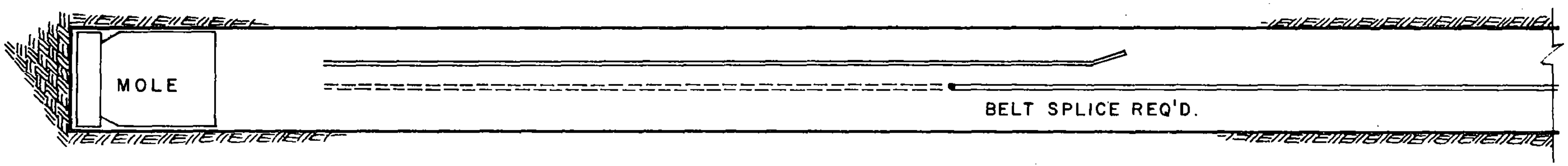
CONVEYOR BELT WIDTH, SPEED, MASS FLOW RATE



SEPARATE CONVEYOR UNITS



FLOATING TAKEUPS



SINGLE CONVEYOR

FIGURE 3-3

THREE TYPES OF CONVEYOR EXTENSION

It is reported that this can be accomplished in a matter of minutes with mechanical splices. The total length of a single belt would be limited by any decrease in belt strength due to the numerous mechanical splices. Surge storage capacity would be required to accommodate the periodic shutdowns for splicing and allow the excavator to continue working. Figure 3-4 shows surge capacity requirements related to mass flow rates for up to 30-minute shutdown periods.

A variation of this method of conveyor extension would be to install a series of complete conveyor units, each one being about the same length as the feeder conveyor. As the feeder is discharged onto the last unit in the series, a new one would be installed ahead of it. When the feeder reaches the end of the unit it is supplying, the new conveyor would be ready to receive the feeder discharge. The erection of the new conveyor units would be a continuous operation in order to keep up with the tunneling advance.

Another method of conveyor extension would be to utilize complete conveyor units with floating-belt take-ups. As the advance progressed, the tail section of the conveyor would follow and the floating take-up pulleys would move to release more belt for material transport. The drive end of the unit would remain stationary. Framing members and idler rolls would be installed as the belt transport length increased. The tail wheel would be mounted on a moving platform.* Brackets and rollers for the permanent sections of the belt would be installed on the wall of the tunnel by crews and special equipment mounted on the sliding floor. A gantry would support the conveyor belt high enough to allow incoming material to enter the forward zone. The conveyor belt would be supported by rollers on the gantry over a long enough length to allow the belt to gradually swing over the permanent rollers mounted on the wall. The sliding floor is inclined to provide a portable foundation for all equipment involved and to provide a switching and unloading area for incoming material. Either rail or rubber-tired vehicles may be used for this purpose.

These techniques have at least one factor in common; they all require a continuous construction effort to maintain a given rate of advance. In most cases, a complete system shutdown would be necessary to complete the installation.

*The moving platform or sliding floor concept developed by Jacobs Associates, San Francisco, California.

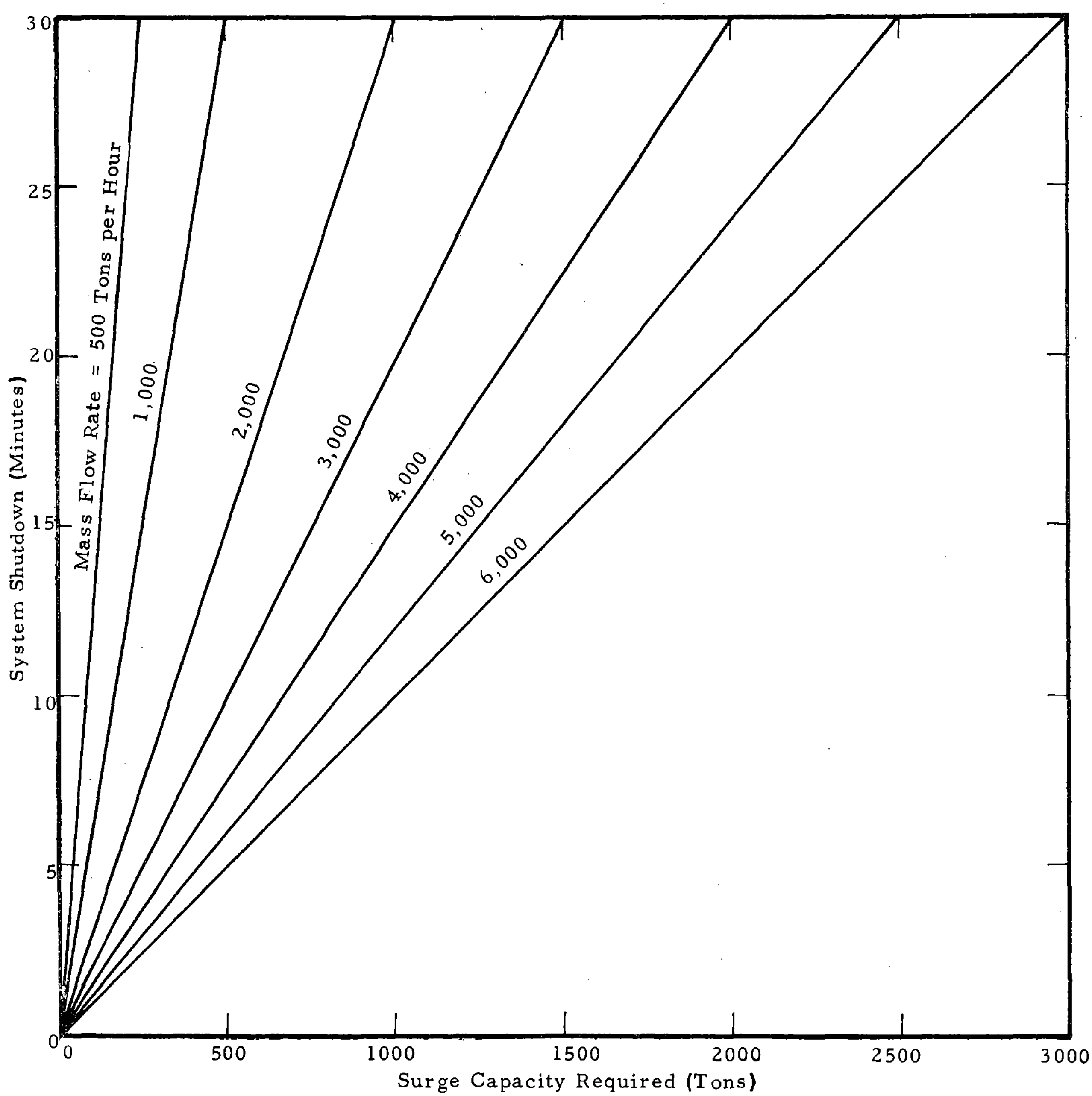


FIGURE 3-4

SURGE BIN CAPACITY REQUIREMENTS

Initial Installation - Problems encountered in the initial installation of a belt-conveyor system would be similar to those found in the extension operations. However, the feeder-conveyor segment, which follows the excavator, would be extended to its predetermined length at the same time the initial sections of the conveyor are installed in the tunnel. This would permit the discharge of muck from the excavator directly into a transfer mechanism, or other transport mode, while the first portion of the tunnel conveyor is being installed.

There are approximately 1,500,000 tons of muck contained in a 20-mile segment of a 40-foot diameter tunnel. Based on a life expectancy of 30,000,000 tons, it can be assumed that a conveyor system could be disassembled and moved to a new location once a given segment of tunnel is completed. It is also assumed that it can be reused in another tunnel segment with little or no modification. It is estimated that such a move would entail about 50 to 65 percent of the installation time for dismantling and removal. The reinstallation in the new location would approximate the previous initial installation and extension operations in labor and time.

Life Expectancy - According to industry figures, conveyor belt life expectancy ranges from 30,000,000 to 60,000,000 tons of material transported. Based on those figures, a conveyor transporting 3,200 tons per hour (the muck removal rate corresponding to a 750-foot-per-day advance in a 40-foot diameter tunnel) would have a minimum life expectancy of about 1,000 days, or 3 years. Idlers and drive components in permanent installations are amortized over a period of approximately 10 years. However, belt replacement can be expected at any time during operation depending on the nature of the transported material. Replacement will relate more to damage from sharp-edged material than to wear. Spare parts requirements for belt conveyors will consist of belting, drive units, idlers, and splicing materials.

Technology - Belt speeds have increased over the years. It is fairly common to see belts operating at speeds up to 1,100 feet per minute as compared to the former limitation of about 650 feet per minute. Advances in the quality of belt materials, as well as in the general durability of belts, idlers, and other components, have contributed to this increase in speed. The use of new types of belt idlers such as the "Limberoller"* has aided in increasing belt capacity and belt life.

*Trade name of Joy Manufacturing Company, New Philadelphia, Ohio.

Belt splicing also has been speeded up. While a permanent vulcanized splice in a 42-inch-wide belt still requires a six-man crew for three 8-hour shifts, a new mechanical splice can be installed on the same belt in a matter of minutes.

Advantages - There are several advantages to a troughed-belt conveyor system which enhance its possibilities for use as a muck removal system. They are:

1. The conveyor can be installed overhead or on the sides of the tunnel, thus releasing floor space for other usage.

2. Capacities can be varied by adjusting the belt speed.

3. If a transfer of materials is required at a shaft station, an elevated surge bin can be used which will also release floor space for other uses.

4. Belt conveyors can transport muck up slopes as steep as 27 degrees (51 percent). This eliminates the need for a different mode of muck transport up an inclined shaft.

Disadvantages - Some disadvantages are to be found in a troughed-belt conveyor system. They are:

1. Use of a belt conveyor for muck handling requires a supplementary unitized method of transport for incoming materials and the bidirectional shuttling of personnel. However, there are instances where belt conveyors have been used to bring in selected materials, such as shotcrete, on the return belt. This requires modification of the return belt and idler arrangement.

2. Where vertical shafts are used for transport of material to the surface, a transfer of material to another mode is mandatory at the shaft station. If some form of closed-belt system could be developed which would operate under the anticipated heavy-load, vertical-distance requirements, this transfer would be unnecessary.

3. Methods of conveyor advance requires a high degree of mechanization and precise timing to maintain a continuous flow of material. Under the most favorable conditions, a brief interruption for belt splicing may be necessary.

Segmented Conveyors

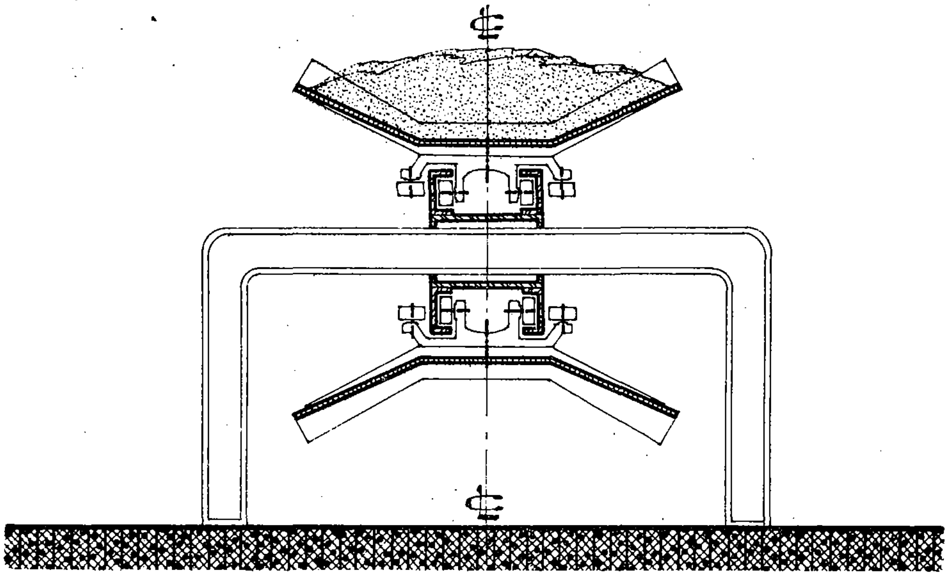
This category of conveyors includes serpentine conveyors and bucket elevators. The bucket elevator in one of its most common forms consists of a chain drive with load-carrying buckets attached to the chain. Apron feeders and apron conveyors which use the same basic configuration to transfer material horizontally can be classed in this category, but they are considered to be short-range transfer mechanisms rather than long-haul material transporters. Restriction of their application to material transfer is mainly die to their extremely heavy construction and resulting high cost. Mass flow conveyors, in which the material is moved through a rectangular metal tube by means of chain-driven, open flights, are also a form of segmented conveyor used extensively in power plant and industrial applications; but because of relatively slow speeds, they appear less suitable to tunneling.

The general characteristics of a segmented conveyor are the continuous loop formed by the transport medium (a basic characteristic of the continuous flow type system) and the fact that this medium, while attached to a continuous drive mechanism, is in separate pieces or segments. Thus, a bucket elevator is driven by continuous chains. A mass flow conveyor operates on the same basic principle, except that the open flights push or drag the material through the enclosing tube.

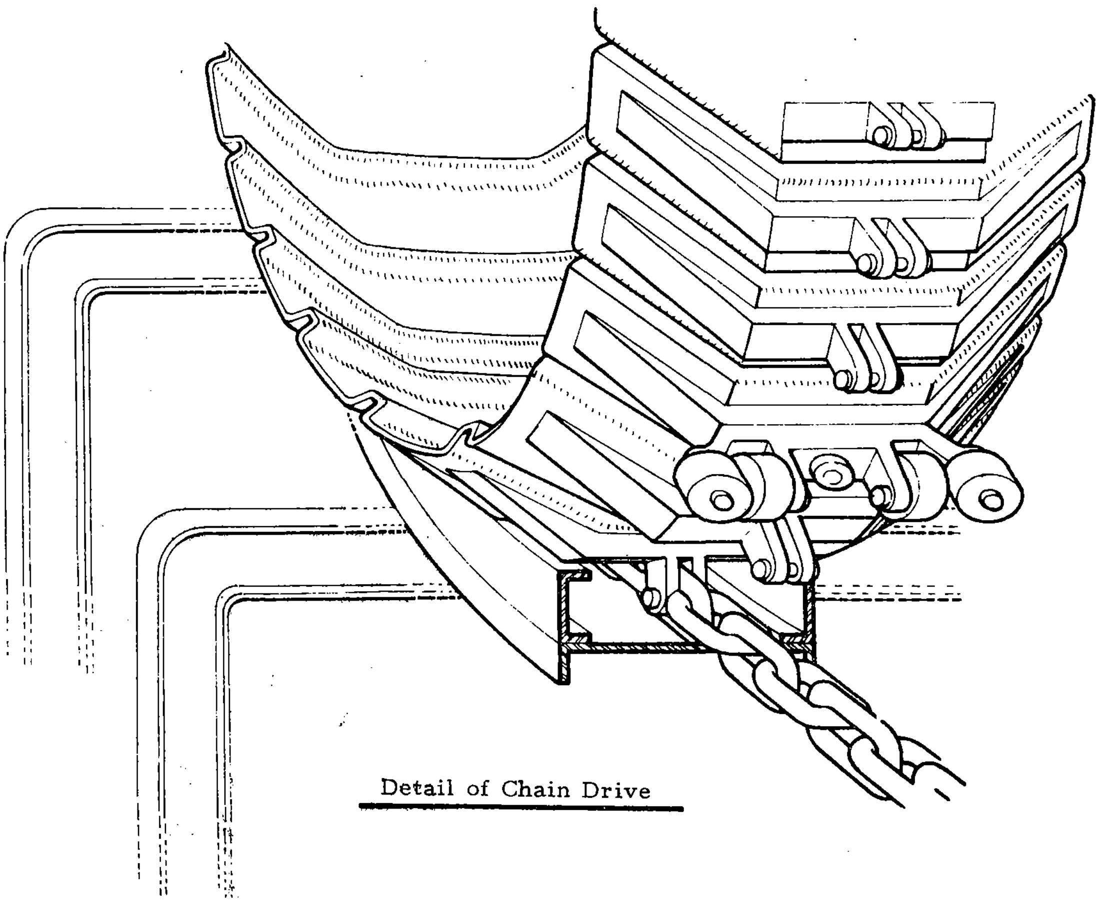
The basic element of a serpentine conveyor is its pan-shaped modular belt. This type conveyor, shown in Figure 3-5, is represented by the Serpentix.* The belt consists of fiberless, rubber sections which are vulcanized to pan-shaped steel plates that bolt together. On the conveying surface, high vertical convolutions are molded into the rubber between the steel plates. When turning curves, these folds allow the inner side of the belt to compress and the outer side to stretch. Comparison shows the serpentine concept to be a modification of the troughed-belt conveyor to achieve improved flexibility, more positive drive, and improved load-carrying capacity but at probable increased cost. Due to the similarity in basic characteristics, the serpentine concept is not evaluated as a separate mode of transport.

Limitations - Bucket elevators are commonly used to lift bulk materials for short vertical distances. Their load capacities are limited by their operating speeds, size of the buckets, and allowable load on the head pulley. Speeds to 465 feet per minute are normally used, and the largest standard buckets average about 1.5 cubic feet each. Material flow rates

*Developed by the Serpentix Conveyor Corporation of Denver, Colorado.



Section Through Typical Installation



Detail of Chain Drive

FIGURE 3-5

SERPENTIX CONVEYOR

of up to 600 tons per hour can be attained with material weighing 100 pounds per cubic foot, but vertical lift rarely exceeds 75 feet. It can be determined from these facts that a bucket elevator application would probably not be practical for the tonnage and lift distances contemplated for high-speed tunneling.

Mass flow conveyors are restricted in the material which they handle. Generally, they are used for both horizontal and vertical transfer of bulk materials weighing less than 100 pounds per cubic foot and of relatively fine particle size with 1-1/2-inch maximum lump size. The capacities of these conveyors rarely exceed 300 tons per hour with maximum speeds of 180 feet per minute. Their vertical lift capabilities are normally limited to about 75 feet. As the maximum performance capabilities of these conveyors are less than for the bucket elevators, their application to rapid tunneling is not considered feasible.

The serpentine conveyor is relatively new, although over 100 installations outside the United States are reported to be in operation. From observation, it appears that a 12-foot radius curve is about the minimum that the conveyor can follow. Thus, if used in a vertical lift application by spiraling around a vertical axis, it would require a minimum shaft diameter of 24 feet.

Undulatory Conveyor

Equipment has been designed in concept to move material along a flexible belt as the belt is given wave-like undulatory movement by the sequenced motion of vertical supports. This motion raises and lowers the belt at predetermined positions along its length in a timed sequence.

Inasmuch as this type of conveyor is modular, it lends itself more readily to continuous extension than the more conventional continuous belt conveyors. This could be a distinct advantage during high advance rate tunneling operations. There is also a possibility that this type of conveyor could be used as a transfer mechanism, as between horizontal and vertical transport modes.

Some advantages of this type of conveyor are:

1. Modular construction which facilitates installation.

2. Can be powered at numerous locations along its length.

3. Can operate around curves and will not malfunction if misaligned.

Some disadvantages which this conveyor has are:

1. Monodirectional in travel.

2. Requires a supplementary transport system for incoming materials and personnel.

3. May have excessive belt wear due to sliding friction between belt and undulating supports and also between belt and material being transported.

PIPELINE SYSTEMS

Pipeline systems can be either hydraulic, using water, a dense fluid, or a slurry of fines as the transporting medium; or pneumatic, using air as the transporting medium. Pneumatic systems can use the tunnel space as the return channel for the transporting medium, thereby avoiding the cost of a return pipeline while providing essential ventilation and reducing the problem of system extension.

Hydraulic Systems

A hydraulic pipeline system for transporting slurried materials is relatively simple in operating principle. A liquid, such as water, becomes the transport medium and can be recirculated from the system terminals if it is not abundantly available. It is mixed with the excavated material in a mixing chamber or tank, producing a slurry which is pumped into a pipeline that carries the slurried mixture to its destination. Here the solids may be separated from the liquid through a dewatering process, or they may be transported elsewhere in the slurried form for further processing. Sufficient system pressure is required to maintain particle transport velocities, and the use of crushing equipment ahead of the mixing operation may be required to obtain the correct particle sizes.

System Components - The main components which are required for the operation of a hydraulic slurry system in a muck-removal application are more numerous than the operational description suggests. If there is a constant and sufficient source of water available, the system can operate without reclaiming the water. However, if water is at a premium, it would be necessary to install a reclaiming system which would consist of a settling tank (or pond), pumps, filters, and a water storage tank with a make-up connection, as well as piping, valves, and controls. This equipment would be located on the surface in the vicinity of the shaft collar, with the return water piping extending down the shaft and through the tunnel to the slurry mixing station.

Slurry mixing tanks, a surge tank, and the pipeline charging apparatus would be located on a movable platform behind the excavator. Muck may be fed to the mixing equipment by means of a belt conveyor, while the water would be fed from the surface unless a sufficient quantity were available from other sources in the tunnel, which is unlikely. Along the tunnel, in-line centrifugal booster pumps, installed at designated intervals, would move the slurry through the horizontal system.

There are several variations in design of a hydraulic hoist system which might be practical depending upon the characteristics of the material to be pumped, the magnituce of the hydraulic head, and the general configuration of the tunnel-shaft complex. For shallow tunnels, a simple installation of a series of low-head slurry pumps, hoisting the material in stages up the shaft, might be the most practical; for deeper shafts where pumps having high hydraulic head characteristics are required, other more sophisticated systems are required to take advantage of the hydrostatic head of the returning water. For example, if an open-ended system is pumping a slurry of 50 percent solids by weight up a 3,000-foot shaft, it is hoisting, say, 50 tons of rock and 50 tons of water every minute. If the loop is closed with the return water line and the hydrostatic head is balanced, then only the power to hoist the 50 tons of rock is required. This, of course, is over-simplification and does not allow for friction and mechanical losses, but the overall power saving is substantial.

Although there are several possible designs of closed-loop systems, only one type is reported to have been installed and operated successfully. The lock-feed system installed at St. Etienne, France, has been operating very successfully since 1960, hoisting 500,000 tons of 3-1/4-inch coal annually.(1) This hoist system, along with a hydraulic transport system for the tunnel are depicted in Figure 3-6, Alternate "A". The transport system shown is the lock-hopper system on which Fawkes and Wancheck(2) of the U. S. Bureau of Mines have done considerable pilot plant testing.

There are two basic approaches to transporting solids hydraulically. One is to mix the solids and liquid and feed the resulting slurry directly into a pump. This is the through-the-pump system. The other approach is to feed only the liquid to the pump and inject the solids directly into the pipeline. This is the lock-hopper system. The advantages of either system depend on the material to be transported and the length of the pipeline. A through-the-pump system has the advantage of simplicity and high capacity, but it is limited to low head and, consequently, short distances. It also has high pump maintenance costs. The lock-hopper system, on the other hand, can be used for deep shafts up to the high-head capacity of conventional high pressure water pumps, can be used for long-distance transportation, and has the advantage of low pump maintenance and high capacity. However, this system requires a rather complex solids injection facility.

Alternate "B", Figure 3-6, shows a reciprocating high head pump system operating with the lock-hopper feed system. This system, because of the limitations of the valve clearances on presently available reciprocating pumps, cannot handle material larger than 1/8 inch at the present time.

The system as shown recovers the energy of the return water by applying it to the opposite side of the reciprocating piston. Such a pump has not yet been built; however, the fundamental principle appears to be sound, and reputable pump manufacturers consider it to be a feasible concept.

It is possible to use centrifugal pumps for vertical lift, but 21 pumps would be required to complete a 3,500-foot lift. The total static head at that depth is 1,515 pounds per square inch for clear water. Piston pumps, which are a type of reciprocating pump, are recommended by pump manufacturers for this application. Return water from the surface could be run through a separate set of valves to the piston rod end of a reciprocating pump, reducing the differential pressure between the pump cavities and partially balancing the weight of the pumped slurry by the weight of the returned water. This would recover the work potential of the return water head, converting it directly into mechanical energy and reducing the overall energy requirements.

Operational Requirements - Certain conditions are necessary for the economical operation of a slurry system; principally, these are the availability of a sufficient quantity of water, a high percentage of fines (50 percent of 200 mesh) in the excavated material, and a specified maximum particle size. If source water is not available in sufficient quantities, used water would have to be reclaimed at the slurry discharge end and recirculated through the system. If the required percentage of fines is not present in the excavated material, a crushing operation might have to be installed ahead of the slurry mixing equipment to produce the fines and reduce the muck to maximum allowable size. If there is no concern over the maximum size, as would probably be the case for cuttings from a mechanical mole, but there are not sufficient fines available, then two other alternatives exist:

1. Fine material can be recirculated in the system, thus building up to the required quantity.

2. Drilling mud as used in the big hole drilling industry can be circulated to maintain a sufficiently dense media.

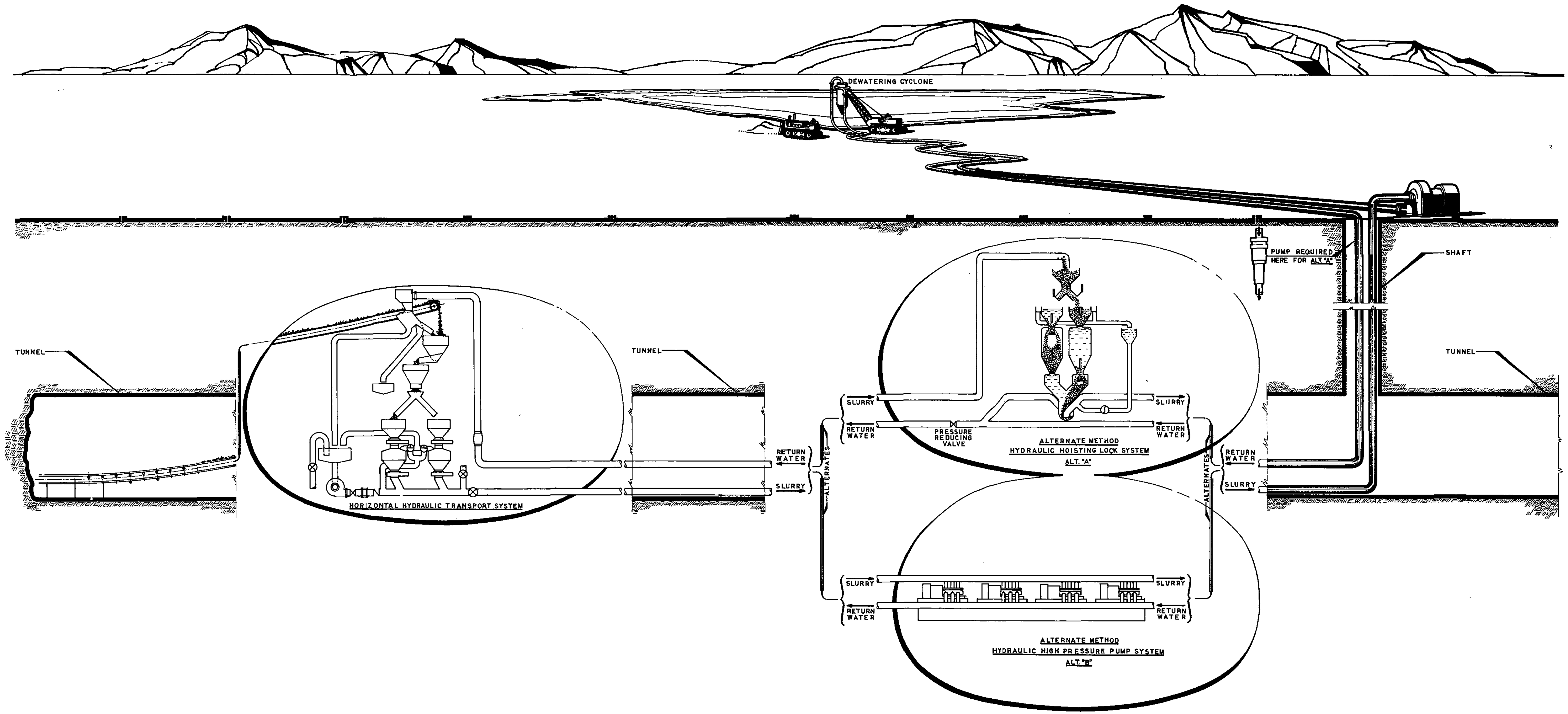


FIGURE 3-6

HYDRAULIC SYSTEM

The nomograph in Figure 3-7 indicates the relationship of gallons per minute required to deliver 1 ton of material of a given density and percent by weight in solution. It also relates material flow to the gallons per minute of slurry required for a given mass flow rate and the slurry flow rate to velocity and pipe diameter. The specific gravity of the mixture at the selected mass flow rate is matched with the required pump discharge head (in feet of water) and then related to the pump shaft horsepower necessary to move it against the head.

Operational Characteristics - Pumping equipment capable of handling muck in slurry form is available in both the centrifugal and reciprocating types. Centrifugal pumps are limited to about 200 feet discharge head and are generally used for low-head, short-haul systems. Reciprocating pumps are used for longer systems due to their ability to operate with discharge pressures in excess of 2,000 pounds per square inch and also to maintain a high volumetric efficiency at any desired flow rate.

To compare the two types of pumps, a tunnel segment 10 miles in length is assumed. A 50-percent weight concentration of solids is to be pumped through a 16-inch diameter pipeline at a rate of 5,500 gallons per minute. This is equivalent to a mass flow rate of 1,000 tons per hour of dry material. Twenty-six centrifugal pumps, utilizing 275 horsepower each, would be required to deliver 5,500 gallons per minute at a 200-foot discharge head. They would be spaced at about 2,000-foot intervals along the 10-mile pipeline. This would be similar to the slurry systems in the Florida phosphate fields where matrix is transported by pipeline to washer plants.

A total of five reciprocating pumps with equal aggregate horsepower (7,150 horsepower) and operating with a discharge pressure of 1,000 pounds per square inch would have the same capacity. However, the application would favor the centrifugal pumps, as their acquisition cost based on total horsepower would be about one-half that of the reciprocating type.

Installation - It is assumed that exploratory drilling to tunnel depths would precede the tunneling effort, with drilled holes spaced at frequent, logical intervals on the surface. Consideration should be given to the possibility of utilizing these holes for vertical access to the surface. The horizontal runs of piping in the tunnel would be appreciably shortened as compared to a system extending all the way to a central shaft. To adequately implement such a plan, two complete pipeline systems would be required. One would be operating through an exploratory hole and advancing down the tunnel while the other was being dismantled and reinstalled in the next hole. The problem involved in moving the vertical-lift pumps and piping at relatively frequent intervals would have to be balanced against the advantages gained from the abbreviated systems.

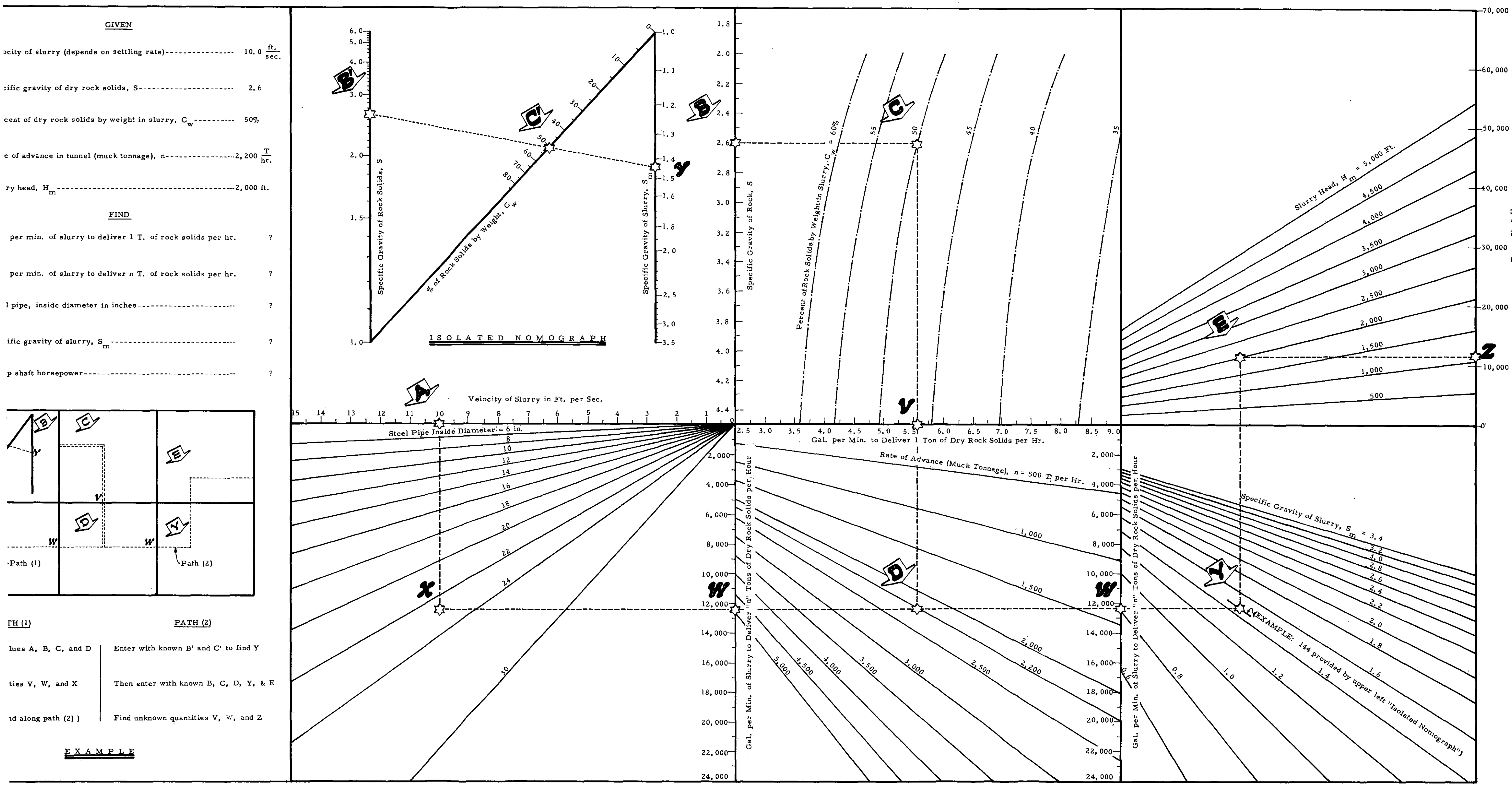


FIGURE 3-7

HYDRAULIC TRANSPORT NOMOGRAPH

The labor required to install a vertical-lift, hydraulic pipeline varies with the depth of the shaft and is not directly related to the diameter of the pipe. No additional time is required for equipment mobilization and demobilization, as it is assumed that the same rig which drilled and cased the shaft would be used for installing the hydraulic piping. It is also assumed that the pumping equipment installation would be concurrent with that of the piping.

About a 500-foot length of tunnel will have to be excavated prior to the installation of the first segment of a horizontal hydraulic pipeline. A temporary material handling system utilizing transloaders as described in Chapter 4 could be employed until the pipeline system was installed. This distance will permit the first horizontal pump to be located a few hundred feet from the vertical station, as well as allow space for the pipe advance equipment on the upstream end.

System Extension - Up to the present time, there are no known instances of rapidly extending a hydraulic pipeline slurry system while in operation. Although the matrix lines in the Florida phosphate mines are moved around, there can be little comparison between the methods used there and the continuous extension requirements dictated by rapid tunneling advance rates. One method which might be applied to pipeline advance, utilizing current hardware and equipment, would require duplicate sets of slurry mixing equipment and manifolded charging pumps complete with valving and bypasses. The valves and bypasses would be left in place as the advance progressed, with the mixing and pumping equipment being "leapfrogged" for each increment of pipe advance. This method would require a high inventory of valves. However, they could be replaced by blank pieces during a system shutdown and reused elsewhere in the system advance.

Any other presently available means of pipeline extension would require a system shutdown while the pumping and mixing apparatus was being connected to the new section of pipe. Slurry systems can tolerate brief shutdown periods, the length of which are determined by the way the slurry settles. If it settles homogeneously with the coarse material remaining with the fines, a longer shutdown period can be tolerated if the two sizes of material were separated. The Black Mesa coal slurry pipeline is said to be able to be restarted after a 24-hour shutdown. It is assumed that this is an extreme case and that the maximum shutdown period with restarting capability for a muck slurry system would be less than 24 hours due to the fact that there could be a less homogeneous mixture than with coal.

Methods presently used for continuously extending pipelines appear to be inadequate as far as keeping pace with the rapid advance rates which are anticipated in tunnel driving. If a hydraulic slurry pipeline system is to be used in a muck transport application, a high degree of automation will have to be reached in the method of continuously extending the system while it is in operation.

A concept for accomplishing continuous system extension is shown in Figure 3-8. Two chambers, grooved to fit the outside diameter of the pipe, are mounted on movable bridges which run on rails, one over the other. Hydraulic rams mounted on the bridges raise and lower the chambers for passing each other. Flexible connections between the pipe grooves in the chambers and the slurry mixing and charging equipment provide a path for slurry and return water flow. The openings in each end of the chambers, which receive the pipe, are sealed by automatic iris valves when not in use. Automatic shutoff valves are incorporated in the lines between the chambers and the mixing and charging equipment. The chamber and bridge trolleys can be electrically driven. The structure supporting this equipment and the slurry mixing and charging equipment are mounted on a sliding floor which follows the excavator.

The following sequence of operation is predicted upon the use of pipe having threaded and coupled ends for quick connection, such as is found in everyday use in the oil field industry. This type of joint would minimize makeup time and eliminate the need for welding.

1. Movable Chamber B is clamped over the open ends of the return water and slurry lines. Both systems are now routed through the chamber, the water to the mixer, and the slurry into the horizontal pipeline.

2. Chamber A is clamped over the forward ends of two new pipe lengths, the other ends of which are forced through the iris valves on the forward end of Chamber B.

3. The slurry and water systems are now rerouted from Chamber B to Chamber A by means of automatic valves.

4. The threaded ends of the new pipe lengths are forced into the couplings on the ends of the first lengths lying in the pipe grooves inside Chamber B.

5. A power-driven wrench or tong positioned between the two chambers completes the joint makeup.

6. Chamber B disengages from the pipelines and repositions itself ahead of Chamber A to repeat the operation.

Another version of joint makeup utilizes piping slightly belled at one end, with the other end having an external resilient ring around it. With this type of joint, operations 1, 2, and 3 would be the same as above, but the remainder would be as follows:

4. The pipe end with the external ring is forced into the belled end of the preceding length.

5. Chamber B disengages from the pipelines and repositions itself ahead of Chamber A to repeat the operation.

6. As the pipe joints depend on a force fit, they can be externally welded to gain greater strength, once free of the chamber.

Present Technology - It is apparent that there has been little or no development in the application of hydraulic pipelines to tunneling. Like most material transport modes, the slurry systems which are presently operating are permanent installations that extend from a fixed loading point to a fixed discharge point. Any system extension necessitates a shutdown period while final connections are accomplished. It would seem that there is a need for development of extension methods that would permit the transport of slurried materials to continue during the operations required for extending the system.

Hydraulic pipelines are being used extensively in modern industry for the transport of slurried material, and in mining there are several instances of slurried material being transported hydraulically over distances of several miles. Examples of this are a 53-mile iron concentrates pipeline in Tasmania which transports 2.5 million tons per year through a 9-inch diameter pipe; a 72-mile pipeline in England which conveys 1.7 million tons of lime per year through a 10-inch diameter pipe; and a 22-mile pipeline in South Africa which handles 1.05 million tons of gold tailings per year through 6-inch and 9-inch diameter pipes. A 273-mile pipeline is under construction in Arizona which is expected to transport 4.8 million tons of coal per year (approximately 600 tons per hour) through an 18-inch diameter line.

However, the present-day use of these systems is usually based on permanent point-to-point installations; and extension of these pipelines are not accomplished with the speed required to keep pace with the projected high tunneling advance rates.

In view of the present state of slurry system technology, it appears that this transport method could be applied to high-speed tunneling operations with relatively little additional research and development work in basic principles. Actual test runs could be conducted using materials similar to the muck which might be encountered in a tunneling operation.

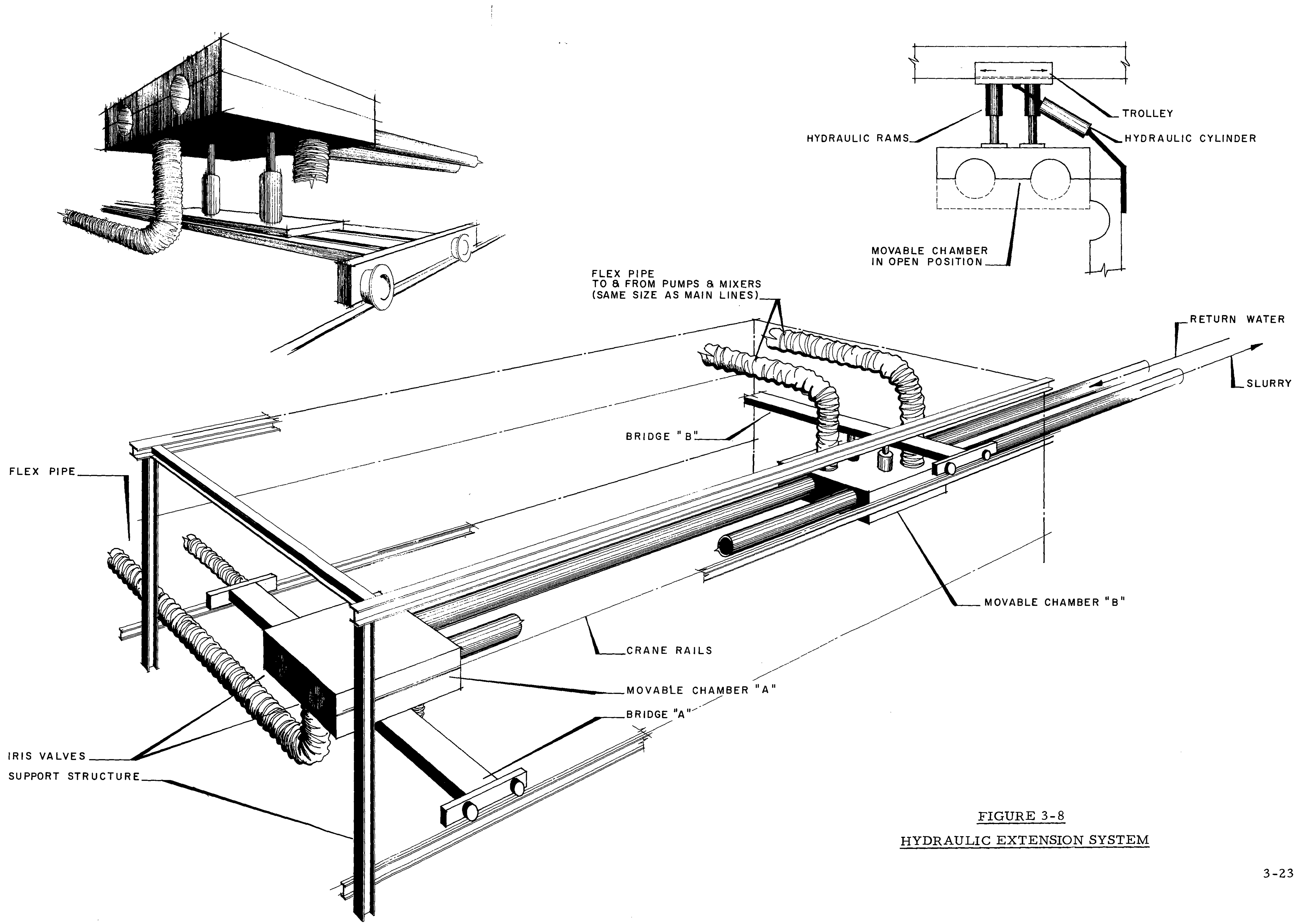


FIGURE 3-8

HYDRAULIC EXTENSION SYSTEM

A need is indicated for the further development of reciprocating pumps so that they will be capable of handling particles larger than the 1/8 inch to which the valve openings now restrict them. Also, research should be conducted toward extending the vertical lift capabilities of these pumps. Further research and development into the use of multistage centrifugal pumps for slurry systems would also be beneficial to the industry. Since this type of pump can generally handle larger-sized particles than the reciprocating type, their future use in hoisting applications might render the need for extensive crushing less critical.

Continued research and pilot plant testing in the area of lock-feed systems are justified since this basic design would eliminate the highly abrasive through-the-pump flow of muck. The requirement for very high pressure pumps would also be eliminated since they can be located outside the tunnel complex at the lowest point of hydrostatic pressure on the return side of the system.

Advantages

1. Hydraulic piping systems are capable of handling muck in the capacity ranges which are commensurate with the projected tunnel advance rates.

2. Hydraulic pipeline systems, with pipe diameters ranging from 6 to 30 inches, occupy relatively small cross-sectional areas (see Figure 2-2) and can be installed on sidewalls or near the roof away from tunnel floor traffic.

3. The system length can be shortened by utilizing intermediate exploratory holes for access to the surface.

4. No transfer of material to other thransport modes is required between the face area and the surface.

Disadvantages

1. A hydraulic muck transport system requires a unitized system to transport other materials and personnel both into and out of the tunnel.

2. If muck particles exceed the maximum size for pumping equipment, crushing equipment must be installed ahead of the mixing and charging units.

3. The required amount of water must be provided from surface sources unless it is present in sufficient quantities in the tunnel. A surface water source would necessitate the installation of a two-pipe system.

4. Proven methods of operating and advancing a hydraulic system concurrently, without interruption, are nonexistent.

5. There is a danger of flooding from a line rupture due to high system pressures required for material transport in vertical lift operations.

Pneumatic Systems

A pneumatic pipeline system for conveying materials would be comprised of several basic elements. An air source, such as a blower, discharges into an air lock injector which forces the material into a pipeline which, in turn, directs the material to its destination. Sufficient air pressure is required to maintain particle transport velocities throughout the system.

At the present time, pneumatic conveying systems are transporting low-density bulk materials such as grain, flour, and ash at rates exceeding 500 tons per hour over distances of a few hundred feet. Pneumatic systems are also in operation which convey wood chips at flow rates approaching 500 tons per hour for as great a distance as 1 mile. One noticeable factor in these systems is the low density of the materials being transported. They all have a specific gravity of less than 1 when dry.

Three-inch rock has been conveyed pneumatically at mass flow rates of 300 tons per hour for a maximum horizontal distance of 1,000 feet. Further research is in progress in which it is expected that 6- to 8-inch material will be conveyed for distances of from 3,000 to 4,000 feet. The present 3-inch lump size in some cases would necessitate the use of a crusher between the excavator and the air lock injector. However, if the pneumatic equipment is developed to handle the 6- to 8-inch sizes, the crusher installation could be minimized; or in certain instances, the need for it would be eliminated.

Pneumatic pipeline systems have the advantage of being flexible in that they can transport material both horizontally and vertically. However, they are only capable of monodirectional bulk material flow and require a supplementary unitized transport system for the conveying of personnel and other types of materials in both directions.

From presently available information, it appears that development of pneumatic systems for handling high density materials over long distances has lagged far behind the development of hydraulic systems. While test installations have been made for back filling worked-out areas in mines, these have been short distance runs (less than 1,000 feet) and at flow rates of 300 tons per hour or less.

A test program was conducted at the AEC Nevada Test Site in 1966,[3] in which various types of pneumatic systems were tested to determine basic equipment capabilities and the effectiveness of line pressure boosters in the placement of sand at distances from 750 to 2,000 feet. Test results ranged from a volume of 9.2 cubic yards per hour with static pressures of 96 pounds per square inch gauge at the loading point and 21 pounds per square inch gauge 2,000 feet distant at the discharge point, to a volume of 17.2 cubic yards per hour with static pressures of 97 pounds per square inch gauge at the loading point and 21 pounds per square inch gauge 750 feet away at the discharge point. In most instances, when booster units were added, they appeared to decrease the volume.

Three types of air booster units were tested. One was similar to that used in pneumatic concrete conveying pipelines, while the other two were similar to the Coanda nozzle design which injects air into the sand-air mix through a circular orifice.

One drawback to the pneumatic system is the rather large amount of power required. A test report of a 1,000-foot, horizontal system conveying material at the rate of 300 tons per hour showed that 800 horsepower was required. This power requirement can be projected to show a consumption of about 10 horsepower per ton per hour per mile. Thus, a mile-long system transporting 3,000 tons per hour would require about 30,000 horsepower. The position taken by some proponents of pneumatic systems that this high rate of power consumption can be justified by the fact that it does away with the requirement for a ventilation system through the suction of air through the tunnel into the blower does not appear to be valid. The power requirement for ventilating a mile segment of tunnel, assuming an occupancy of ten men and a ventilation air volume of 4,000 cubic feet per minute would be about 10 horsepower, a quantity of much less magnitude than that for a pneumatic material transport system.

Pneumatic system possibly could be used to advantage in a vertical-lift application where the maximum distance was about 1,000 feet. If the concept of utilizing exploratory drill holes for the vertical lift were followed as depicted in Figure 3-9, the pneumatic method could be very competitive with other types of vertical-lift transport in the 300-ton-per-hour range. This assumes that the vertical exploratory holes were

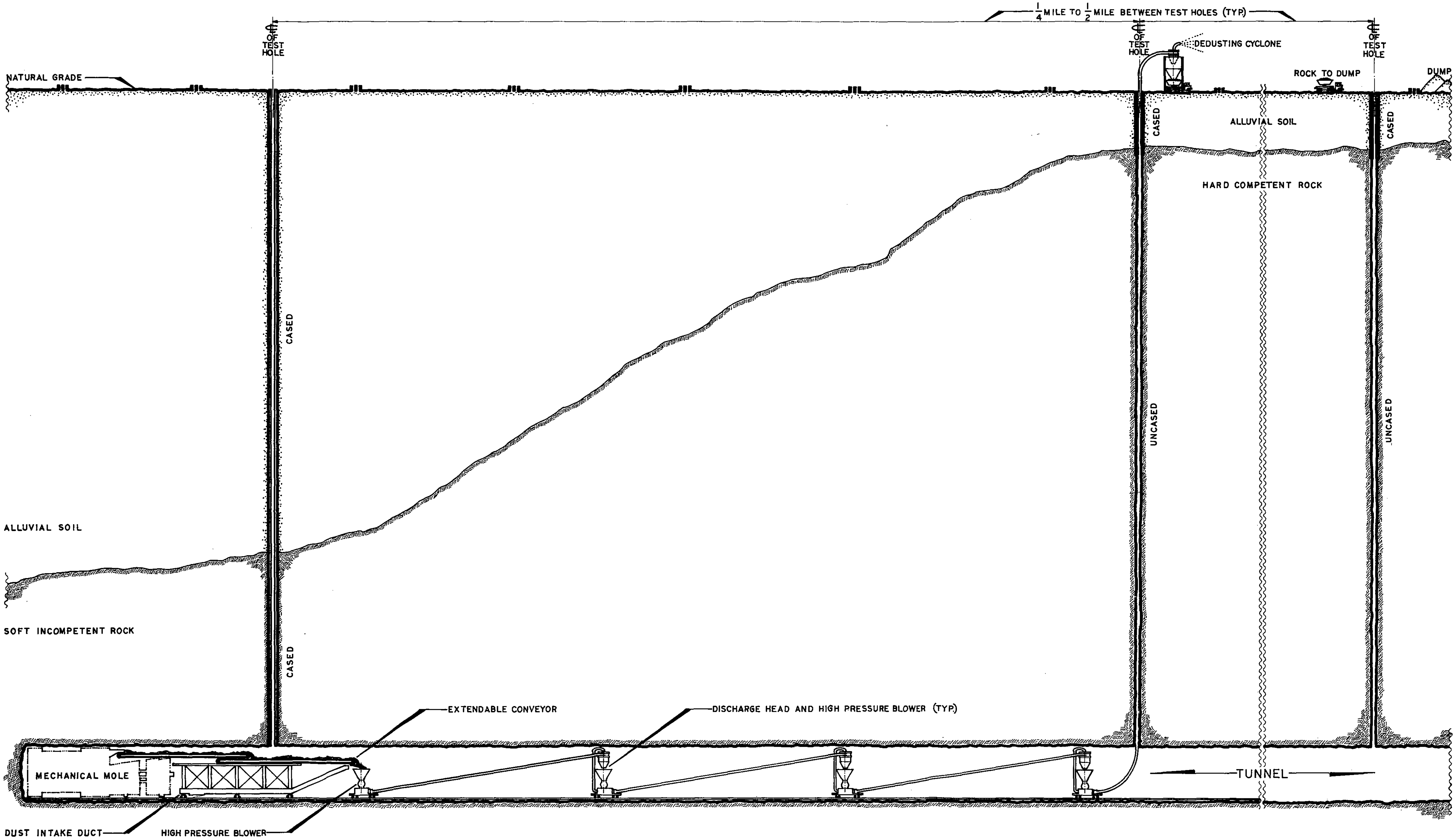


FIGURE 3-9

PNEUMATIC SYSTEM

reamed and cased, where required, to 14 inches in diameter. No casing would be installed where the surface of the hole was adequate.

If the drill holes were spaced at about 1/4-mile intervals, the horizontal tunnel muck transport could be a series of 1/4-mile pneumatic systems or a belt conveyor. Either system combination would support all rapid advance rates in a 10-foot diamter tunnel and a rate of up to 300 feet per day in a 40-foot diameter tunnel.

In the course of research and development, attention has been given to pipe wear. In a test of ten different kinds of pipe material, it was observed that a two-layered pipe appeared to be more abrasion-resistant than others. The inner layer was a very hard steel alloy, and the outer layer was a mild steel. However, in a pneumatic system incorporating a transition from the horizontal to the vertical, the elbow at the base of the vertical run could be subjected to excessive wear due to the change in direction of the flow of the transported material. This might necessitate the use of a transfer system at that point making the vertical portion a completely separate system.

Advantages

1. A pneumatic system can be used in either horizontal or vertical application, or both.

2. The system occupies a minimum of tunnel cross-sectional area and the pipe can be installed in any convenient location.

3. No transfer of materials is necessary except if excessive wear is anticipated in the base elbow.

4. The vacuum drawn by the blower assists in tunnel ventilation.

5. In case of a power loss, the material can be picked up from the bottom of the pipe by permitting the air to reach transport velocity before injecting more material when restarting the system.

Disadvantages

1. Very high horsepower requirement.

2. A pneumatic system requires a companion unitized transport system to bring tunnel support materials and personnel from the surface.

3. Operations are generally limited to the transport of dry materials.

4. Constant abrasion from the transported material inside the pipeline causes undue wear. However, the blower units are not affected, as the material is injected downstream from the blower discharge.

5. Crushing equipment is usually required to reduce the material below maximum particle size.

Capsule Pipeline Systems

This method of bulk solids transport is being developed as a result of successful operations in fluid and slurry pipeline systems. Research programs are being conducted in Canada for capsule pipelining of rigid and semirigid capsules as well as for paste slugs. These programs include studies and tests of these forms of capsules in relation to the transport of coal, sulfur, potash, steel, and mineral ores. Research in the transport of encapsuled and compressed waste materials is currently in progress in the United States.

Tests have ranged from the movement of a 514-pound, 16-inch diameter capsule through 109 miles of crude oil pipeline to the flow of coal paste slugs (70:30 w/w coal-water paste) in a light mineral oil through a 1-inch inside diameter, 70-foot closed-loop system. It has been noted in a number of the tests that the capsules with diameters close to that of the inside of the pipe nearly always move faster than the average liquid velocity in the pipe, since they occupy an area in the pipe where the liquid velocities are higher than average.

Power requirements appear to be lower for capsule transport than for slurry transport, except where the slurries have very small particle sizes. Methods of capsule injection into a pipeline system and retrieval at the destination end, as well as devices for bypassing within the pipeline system, are under development in the Canadian program. It appears that problems of system extension and loading material into the system will be at least as severe for capsule systems as for the slurry system. Because of the early phase of development of this technology and the fact that it represents a modification of the slurry transport concept, capsule pipeline systems were not included as a distinct mode of transport for comparative evaluation.

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CHAPTER 4

UNITIZED TRANSPORT SYSTEMS

The characteristic that distinguishes the unitized transport systems from the continuous flow systems is the separation of the material being transported into discrete quantities which are carried by mobile units or modules of the transporting system. These modules may move as individual units or as trains of interconnected units. The modules may travel on fixed guideways such as rails or they may be free vehicles such as trucks. Although free vehicles have greater maneuverability than guideway modules, they are often restricted to prepared roadways in order to attain the required speeds.

In Chapter 2, guideway systems were categorized as conventional rail systems with locomotive, side-wheel or cable drive, siderail systems, monorail systems, and hoist systems. Hoist systems are suitable only for raising or lowering materials between the tunnel and surface, while some of the rail systems may be suitable for use in both the horizontal and vertical attitudes of transport. Free vehicles were categorized as transloaders suitable for short haul transport and trucks for long haul.

Unitized systems are more flexible in application than continuous flow systems because:

- Modules can be added to or removed from the system to vary the system capacity.
- Modules can operate easily over a range of speeds to adjust to variations in flow rate requirements.
- Special design modules can be used for transporting various types of materials.

This flexibility offers the possibility of using a single system in a tunneling application for the transport of both inbound and outbound materials.

The operation of unitized systems is cyclic because each module must be loaded, moved to its destination, unloaded, and returned to the loading point. Although attempts are made to perform these operations as rapidly and continuously as possible, the cyclic operation remains, particularly at the loading point for bulk materials and for both loading and unloading of discrete materials. Under the highly congested conditions in the near-face zone of a tunneling operation, turnaround of transport modules is difficult at best and often impossible. The alternate to turnaround of modules is a system which "dead-ends" in the near face zone. A dead-end system must be cyclic in operation since the transport modules must come to a complete stop before reversing direction.

To achieve the material flow rates required for rapid advance of the tunnel face, several trains or many individual load-carrying modules would be required to operate simultaneously in the system. The number of units used for a given material flow requirement is determined by an economic trade-off between the cost of the inventory of units in the system and the increased cost of higher quality guideway or roadbed, and more sophisticated controls required to achieve higher speeds. Speeds up to 40 miles per hour may be required for some unitized systems. To safely operate any of the unitized systems, it will be necessary to maintain complete control at all times over the synchronized movement of the transporting units. This can best be performed automatically. Several methods of automatic control have been developed for rail systems, some of which are presently in use in the mining industry. These are visualized as being adaptable, with modifications, to other unitized modes of transport and to the special requirements for use in tunneling.

One method of system control is by radio where operators on the ground transmit signals to a locomotive by means of back-pack radio transmitters. Another method is the supervisory control system in which train movements between points are controlled by operators who ride the locomotives but are subject to override by a central dispatcher. In these types of systems the human element exercises control over the operations, whereas a completely automatic system is preferable from both a safety and operational point of view.

A programmed control system, which is being successfully operated at the Carol Mine in Labrador, appears to be adaptable for use in high-speed material transport operations. The trains respond to a complete sequence of coded signals in performing the required haulage tasks. The signals are transmitted through the rails as low voltage alternating current. Coils on the locomotives and tail cars of each train receive the signals and actuate relays and electropneumatic valves to produce locomotive response. The simultaneous operation of four trains is now controlled in this manner at the Carol Mine. It is reasonable to assume that a similar program control system could be adapted to a locomotive system for muck removal with a minimum of modification.

The programmed control concept also appears to be applicable to other unitized modes of transport such as the side-wheel drive, siderail and monorail systems and with greater modifications, possibly to some free vehicles.

CONVENTIONAL RAIL SYSTEMS

Conventional rail systems have transport modules or cars mounted on wheels (usually steel) which ride on top of a track consisting of two parallel rails mounted on cross ties supported by a suitable surface. A commercial railroad illustrates this type of guideway system.

General Characteristics

Systems of the conventional rail type used in mining and tunneling operations generally utilize a single-track layout with passing sidings. Transport in both directions is accomplished by having one train wait on the siding until the other passes by on the main track. This method appears to be less expensive in capital cost than one using a double-track system throughout the length of the tunnel. However, it is doubtful if a single-track system would support the maximum muck-removal rates due to the fact that several trains would be operating concurrently in both directions.

A double-track layout could include cross-overs spaced at intervals along the tunnel to permit trains to bypass a stationary train on-loading or off-loading or being repaired. This would also permit isolation of a section of track in case of track failure or derailment of a train. Although this arrangement would permit continued operation of the system, the system capacity might be reduced in some cases due to the bidirectional traffic on a single track over the section being bypassed. It appears that a double-track conventional rail system at the present state of development could handle the tonnages required for the rapid tunnel advance rates considered in this study if problems of rapid loading and synchronized flow of rail cars are solved satisfactorily.

The nomograph in Figure 4-1 shows relationships between bulk material removal rates, car dimensions and capacities, and loading frequencies. Figure 4-2 depicts the percentage of the tunnel cross-sectional area which a single-track rail system would occupy in tunnels of given sizes. For example, at the maximum muck rate of about 7,000 tons per hour (approximately 4,700 cubic yards per hour) produced by a 40-foot tunnel advancing at 1,500 feet per 24-hour day, approximately one 8- by 8- by 30-foot car per minute would need to be loaded. A double-track system with cars of this size would occupy approximately 60 percent of the cross section of a 20-foot tunnel and approximately 16 percent of a 40-foot tunnel.

Although Figures 4-1 and 4-2 were developed specifically for conventional rail type transport modules, they can be applied to other unitized modes of transport since the basic relationship between module shape, capacity

FIGURE 4-1

BULK CAR CAPACITIES

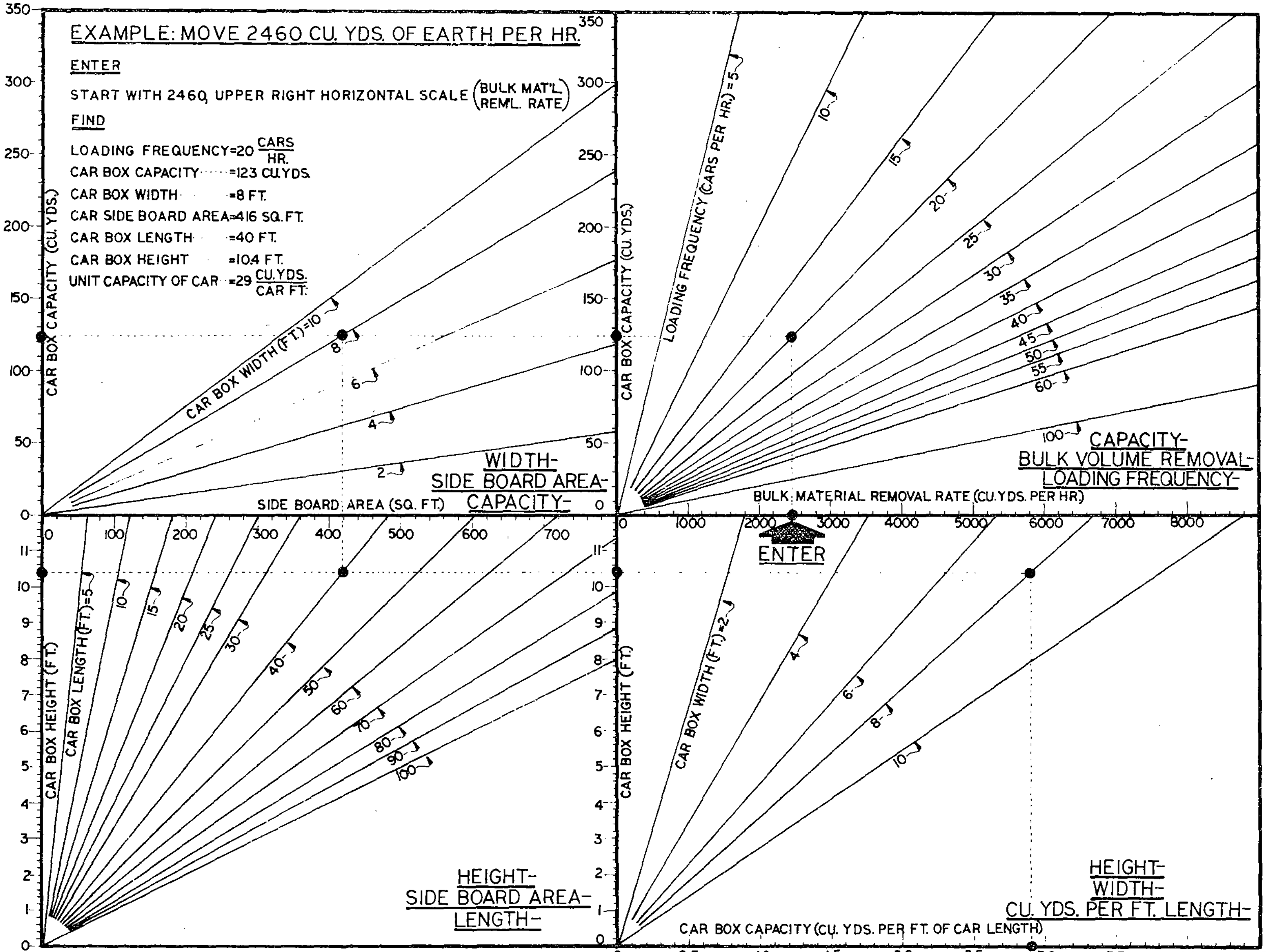
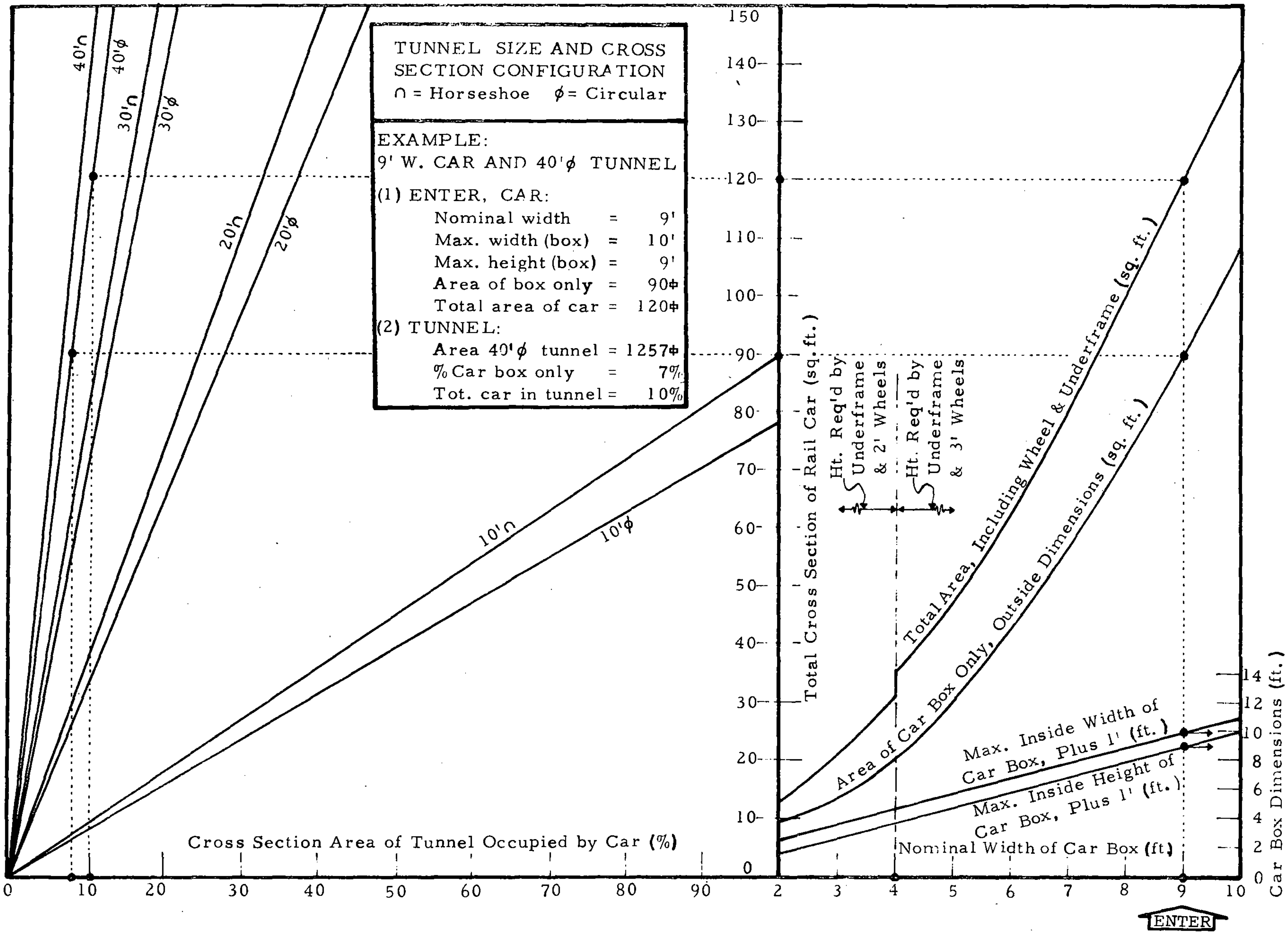


FIGURE 4-2

TUNNEL OCCUPANCY FACTOR



and loading frequency is the same. When applying Figure 4-2 to other modes, a proper allowance should be made for space occupied by the guideway system to obtain the correct occupancy factor.

Rail system capacities are flexible and depend on:

- Capacity of the cars
- Number of cars in a train
- Number of trains in the system
- Length of time per cycle

The cycle time is dependent to a great extent on the speed of the train, although loading and unloading times are important factors. In general, maximum speeds are determined by the track quality, the grade and congestion of the tunnel segment being traversed, and load conditions. Speeds up to 20 miles per hour loaded and 33 miles per hour empty can be expected with the present technology. A double-track system operating at these speeds over a 7.5-mile run with six trains of ten 100-ton capacity cars, each pulled by a 100-ton locomotive could be expected to achieve a maximum transport rate of 5,400 tons per hour. This would be sufficient to support an advance rate of the order of 1,200 feet per day in a 40-foot diameter tunnel. However, with a smooth roadbed and level and well-gauged tracks, a four-train system, each with ten cars of the same capacity and with the same locomotives, could deliver the same amount of material over the same distance. This would require an overall average speed of 35 miles per hour, with maximum speeds of 40 miles per hour. In either of these cases, a carefully controlled running schedule would have to be maintained in order to permit the trains to keep their proper intervals and sequence.

Rolling Stock - Muck cars are manufactured with a wide variety of capacities, sizes, and features. The larger cars, which due to their greater capacities require fewer round trips, appear to be capable of handling high mass flow rates. Some can be automatically dumped, either sideways or from the bottom, without coming to a stop. Cars and their dumping arrangements include the rocker dump, the bottom dump, the end dump, the Granby or automatic roller dump, the air dump, and other nonstandard types. Capacities vary from 1/2 cubic yard (about 1 ton) to the large 100-ton cars. Widths range from about 2.5 feet to as much as 11 feet. The tendency to retain a low profile with regard to overall car height seems to be general, with the exception of the smaller cars (1-ton to 5-ton capacity) where the height is considerably greater than the width. Wheels as small as 10 inches in diameter are used on the small cars and can be 24 inches in diameter or more on the large-capacity cars.

Track gauges range from 18 inches up to 5 or 6 feet (normal commercial rail gauge is 4 feet 8-1/2 inches), depending on the requirements. Special cars for hauling construction materials and tunnel lining materials are in use at the present time.

Rocker dump cars feature a rounded-bottom body with flaring sidewalls and vertical end walls. The dump mechanism consists of a convex-toothed rack attached to each end of the car frame which engages a semicircular gear mounted on each end of the car body. The mechanism is actuated by a foot treadle and a slight push which tilts the body to the dump position. After dumping, the body is manually pulled back to the upright position. Car capacities generally range from 20 to 40 cubic feet.

Bottom dump, or hopper, cars are in everyday use in industry, commercial railroad operation, and mining. Capacities range from 1 or 2 cubic yards to over 100 cubic yards. The dumping arrangements vary from a clam-shell type body, which requires a dump block at the side of the track to actuate the dumping mechanism, to the automatic hopper-type dump car which is normally seen in commercial railroading. One advantage to be gained using a bottom dump arrangement at a vertical shaft station would be that the track hopper surge bin need not be as wide as it would if side dumping cars were used.

End dumping cars generally are found in the small-capacity range with manually actuated dump mechanisms. The car body is hinged at one end and tipped by means of a lever lock release.

The Granby-type car is in common use in the mining industry. It is equipped with a dump roller which tilts the car body when riding over a dump block. This mechanism also can be automatically actuated by pneumatic, hydraulic, or electrical means. These cars can be obtained in a variety of designs and capacities to suit special applications.

Air dump cars can be unloaded while in motion with the dumping mechanism being actuated from the locomotive. Telescoping air cylinders under the car body raise it to the dumping angle, and the sidewall folds down automatically. These cars range in capacity from 30 to 60 cubic yards level load.

Standard cars, with no dumping capabilities, are generally used with a rotary car dumper. They range in capacity from 5 cubic yards to the 100-cubic-yard gondola cars used on commercial railroads. Inasmuch as these cars require large, expensive unloading equipment, it is doubtful that they would suit the tunneling application.

Roadbed and Trackage - Tracks in tunnels and mines generally are laid on questionable roadbeds making it difficult to maintain alignment, and rolling stock clearances appear to be minimal. This results in comparatively slow speeds of haulage. Switching is usually done manually, with trains proceeding at a slow pace due to possible misalignment of the rails.

To sustain a train speed of 40 miles per hour, a smooth, firm roadbed is required. Building this bed to support rapid tunneling advance rates presents a problem. Assuming a 22-foot bed width is required to support a double-track system in a 40-foot circular tunnel, approximately 142 cubic yards of gravel (or other suitable material) per foot of tunnel length would be required to form the track bed. Another means of supporting the track in a circular tunnel would be to lay steel beams across the invert and secure the rails to them. A continuous vertical support would be required in order to decrease the length of cross-beam spans. It might be preferable to lay sections of prefabricated supports with tracks mounted on them. This might serve to increase the speed of the track laying operation. In a horseshoe or vertical-sidewall tunnel, this problem would be negligible, as the track could be laid with conventional ties and minimal ballast on the tunnel floor. In either case, the track would have to be gauged and aligned with much greater accuracy than is the present practice during tunnel construction.

Technology Limitations - Rail systems in present-day tunneling are limited in operating capability. Some contributing factors are faulty trackage, manual control, and inability to climb grades steeper than 4 percent. The need for rapid and accurate track laying methods, as well as for automatic control systems, is apparent if conventional rail systems are to be used for transport in tunneling operations. There is also a requirement for a method of operating on grades steeper than the present 4 percent maximum.

If these needs are satisfied and further developments are attained in the area of rapid car loading, it is possible that a conventional rail system could be a major factor in rapid tunneling operations. It also appears that cars could be developed which would handle both muck and tunnel construction materials with little modification required for either type of load.

Propulsion - Conventional rail systems powered by locomotives which depend on friction between the steel wheels and steel tracks for traction have a limitation of about 4 percent on the grades they are able to climb with a load. This requires either a transfer of materials to another transport mode at a vertical or steeply inclined shaft or, where there is a less severe slope, the use of some type of power assist to get the cars up and down the grade. Two basic approaches have been used to alleviate this grade limitation.

One approach is to provide the propulsive force to a train of cars through electrically powered, rotating, rubber-tired wheels mounted along the sides of the track in such a manner that they bear against the sides of the cars. This technique, identified as the side-wheel drive, is relatively new, having been in use only a few years in special applications. The other approach makes use of a moving cable to which the individual cars are attached as illustrated by the use of cable cars for public personnel transport in hilly areas. Either of these propulsion techniques could conceivably be used to assist locomotive propulsion or to drive an independent conventional rail system.

Each of these methods of propulsion (locomotive, side-wheel drive, and cable drive) is used to identify a transport mode which is discussed and evaluated in this study.

Locomotive Drive

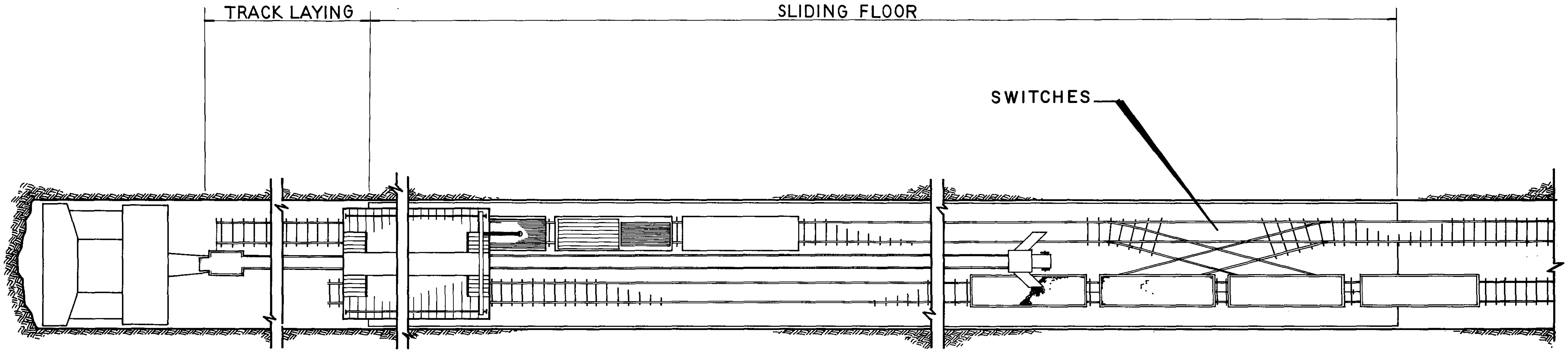
Figure 4-3 shows a concept of the near-face material handling equipment necessary for conventional rail systems handling both muck and incoming material. The loading system concept* rolls on the permanent tracks which are laid ahead of the car loading and unloading stations. Short conveyor sections are used to bring muck to the loading stations. The track-laying area, at least 130 feet long, is ahead of the sliding floor section and is bridged by the conveyor system. Incoming material is transported on cars which are ahead of the muck cars. They are unhooked, left for unloading, and returned on a later train.

Figure 2-2 shows typical cross sections for rail systems installed in various size tunnels.

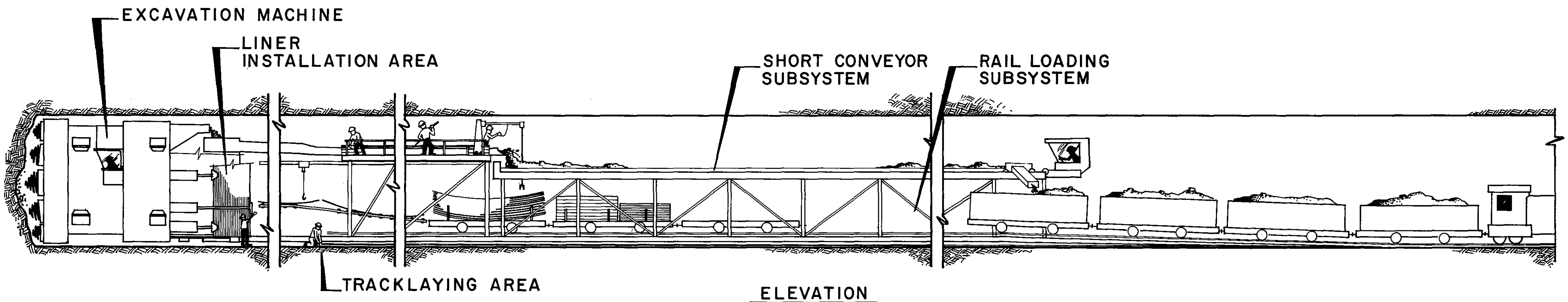
Locomotives are manufactured with a variety of power sources, including diesel, diesel-electric, battery, and electric types. They are produced in all ranges of horsepower and weight; and within the scope of present technology, they can haul trains at the speeds required for the higher rates of tunnel advance.

The use of diesel locomotives is quite prevalent in mining and tunneling operations. They are produced in the haulage capacity ranges which are necessary for the more rapid face advance rates. Diesel locomotives also have been adapted for mechanized operation and automatic control.

*Developed by C. S. Card Corporation, Denver, Colorado.



PLAN



ELEVATION

FIGURE 4-3

LOCOMOTIVE DRIVE SYSTEM
(Near-Face Zone)

Storage battery-powered locomotives are used where the haulage requirements are not dependent upon high speeds or large capacities. Since the maximum speed at which this type of locomotive is usually operated is about 8 miles per hour and the maximum weight is about 8 tons, it appears that a battery-powered locomotive system would not perform satisfactorily in a situation requiring hish capacity transport rates.

Electric locomotives used in underground applications are usually powered through a trolley wire system. These locomotives are available in sizes up to 50 tons and with speeds in excess of 10 miles per hour at the rated running drawbar pull. It appears that this type of locomotive could be used in supplementary haulage applications, such as for tunnel support materials and personnel, where the muck transport is accomplished by a continuous-flow transport mode. However, consideration should be given to the fact that the trolley wire or third rail must be advanced with the track extension and that there may be certain safety hazards involved in accomplishing this, which might make the use of electric locomotives less attractive than others.

Diesel-electric locomotives generally are produced in larger sizes than are required for muck-removal operations. Their main field of operation is commercial main-line hauling, and to consider their use in a tunneling transport system could be a misapplication.

Life Expectancy - Locomotives have been known to be amortized over a 17-year period. In some cases, their general durability and rugged construction have enabled their usefulness to be extended beyond that period.

Much the same can be said for rail cars. Aside from car body damage, which can usually be repaired by patching, the major types of repairs would be wheel and bearing replacements.

Advantages -

1. Locomotive systems are flexible with regard to hauling capacities. The addition or deletion of cars or trains is all that is required.

2. Present technology can support maximum tunnel advance rates on horizontal runs.

3. Adaptable to several car-loading methods, most of which are in use at the present time.

4. A variety of material transfer mechanisms can be used at shaft stations or wherever required.

5. Can transport both outgoing and incoming materials.

6. Easily adaptable to automatically controlled operation, and there is an abundance of operating experience available.

7. Methods of track extension for locomotive systems generally are less complex than the guideway extension methods required for other types of unitized systems, except for free vehicles.

Disadvantages -

1. High-speed, loading equipment required in the near-face zone contributes to congestion.

2. Occupy a relatively large cross-sectional area compared to continuous flow systems.

3. The high speeds (40 miles per hour) necessary to sustain rapid muck removal rates require ideal roadbed and track conditions as well as sophisticated control systems.

4. Unless an inclined shaft with a power assist is used, the transported material must be transferred to another mode in order to reach the surface.

5. Material transfer facilities require a large area.

Side-Wheel Drive

Figure 4-4 shows a concept of material handling equipment in the near-face zone necessary for the side-wheel drive system. The loading system is mounted on a sliding floor which bridges the permanent track. A gantry supports conveyors bringing muck back to the loading stations. Clearance is provided to allow incoming material to enter the forward zone.

Figure 2-2d shows typical cross sections for the side-wheel drive system installed throughout the length of the tunnel. If this system is also used to lift material through an inclined shaft, the installations at the shaft station and in the inclined shaft are similar to the equipment in the horizontal segment of the tunnel, except power stations are more closely spaced.

The side-wheel drive system, which operates on conventional tracks of about 24-inch gauge, utilizes a series of pedestal-mounted, motor-driven, rubber-tired wheels located on both sides of the track. The wheels rotate on a vertical axis and engage both sides of the rail cars, pushing them

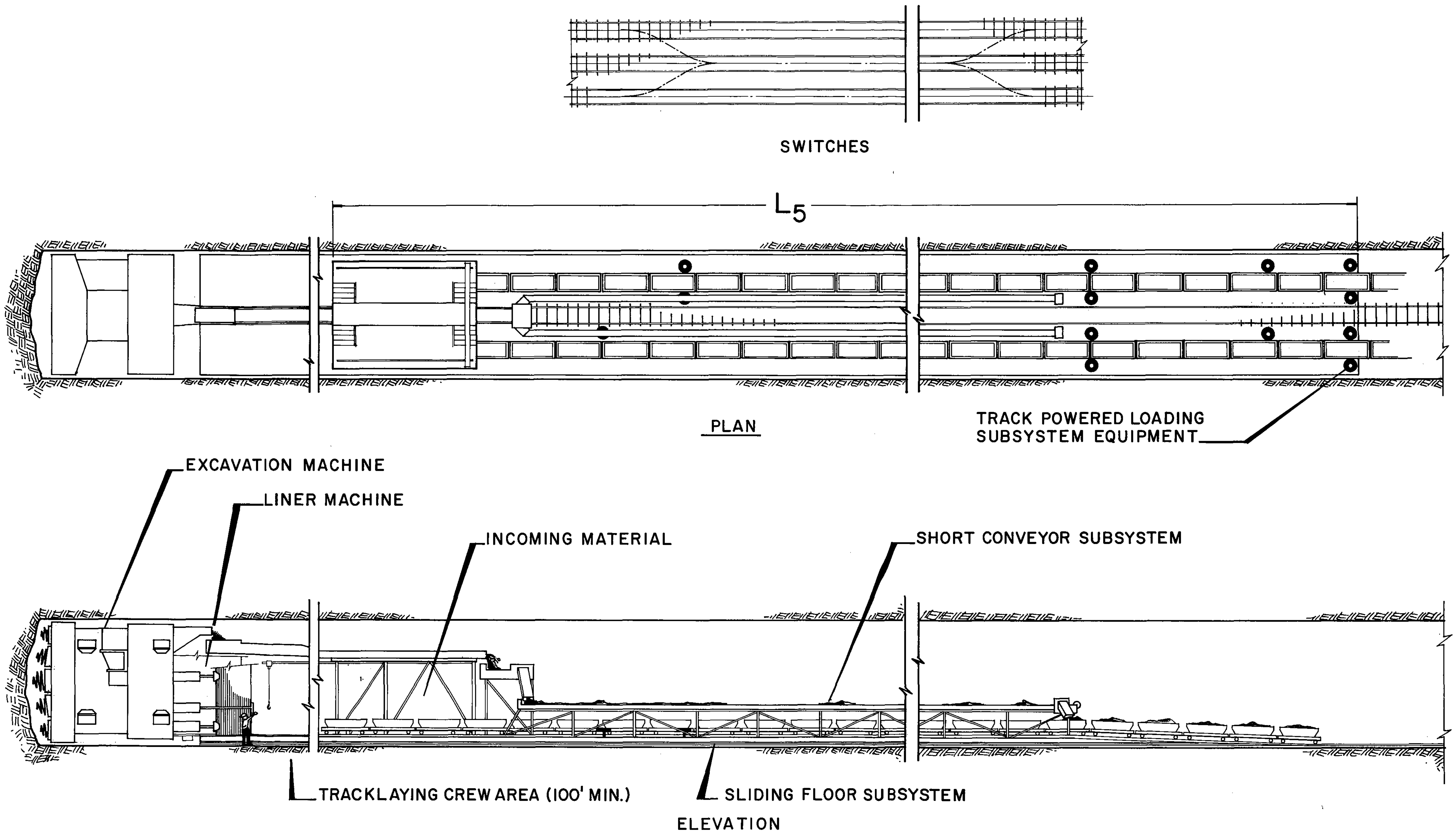


FIGURE 4-4

SIDE-WHEEL DRIVE SYSTEM
(Near-Face Zone)

along in sequence. The longitudinal distance between the drive wheels is such that when the last car of a train is leaving one set of drive wheels, the first car is already engaged with the next set, thus forming a continuous drive system. If used for horizontal transport propulsion, the side-wheel drive system would require more installed equipment, both initially and during system extension than required by a locomotive-powered rail system. In addition to the tracks and roadbed, the drive-wheel units would have to be installed at the regularly prescribed intervals which could increase the system extension problems. If used for propelling trains of cars in an inclined shaft, in conjunction with conventional locomotive propulsion for horizontal runs, the side-wheel drive system, due to its ability to climb steep grades under load, would overcome the grade limitation of the locomotive-powered system. An example of the side-wheel drive system has been developed and placed in operation by a French company;* however, it is understood that arrangements could be made to have it fabricated in the United States.

The three installations which are now operating in the mining industry, two in New Caledonia and one in France, are capable of transporting from 360 metric tons per hour to 900 metric tons per hour, with track gradients ranging from level to 38 percent. Research and development by the manufacturer is presently underway, which could result in an increase of system capacity up to 10,000 tons per hour and the ability to climb grades up to 100 percent or more.

The operation of the side-wheel drive systems now in use is as follows. The cars, mounted on axles with free running wheels, are coupled together into a continuous trough train normally ranging between 650 and 1,300 feet in length. The number of trains in a system is dependent upon the number of cars in a train, the distance to be traveled, the train speed, and the material transport requirements.

The trains usually operate on a two-track, narrow-gauge system. Driving force is obtained from fixed driving stations spaced on the basis of one station per train length less the few feet as required for overlap. Each train is alternately pulled and pushed by each successive driving station. On an incline, the number of driving stations is increased according to requirements so that ten or more driving stations may be simultaneously propelling a single train.

*The SECCAM system developed by Societe Industrielle De Lattre Le Vivier, France.

The type of driving station presently in use is composed of two gear-motor powered turrets each equipped with an automobile type, pneumatic-tired wheel located on both sides of the track. The trains which run between these wheels are propelled through the pressure of the rotating tires against steel bearing plates mounted on the sides of the cars.

Based on data from existing installations, where the drive stations are equipped with synchronous motors, the maximum slip variations are about 8 percent between empty and loaded trains. Any discrepancy in train sequence, as a result of this slippage, is corrected by a regulating station. This is a drive station controlled by a time relay which is tripped by each train passing through, with the slower ones controlling the length of the intervals between trains.

Present operating speeds range from 16 to 30 feet per second (11 to 20 miles per hour). It is expected that higher speeds can be attained with future developments. On downgrades power is generated at the drive stations by disengaging the coupling gears to allow the motors to act as generators. The brakes are either of the automotive type actuated by gravity-operated hydraulic accumulators with solenoid valves or of the electromagnetic type. They provide for both dynamic and static braking. On upgrades braking action is replaced by antifree-wheeling devices to prevent rollback.

All control and operating instruments and equipment are grouped on a central control panel. In addition to the conventional electrical protective devices, the basic safety element is the drive wheel speed control which is actuated by a speed detector. Any one of the protective controls will stop the system upon being actuated. The control panel also contains electronic surveillance instruments for each drive station.

The track is approximately 24-inch gauge, and the rails are in the 25-pound class. In most cases steel ties are used. These act as supports for check rails which run parallel to and above the track and engage idler wheels to prevent the car wheels from leaving the track on steep grades.

A loading system, with either two or four tracks, served by one or more feed conveyors similar to the locomotive-drive loading sytem would be applicable to the side-wheel system. For unloading, the train can be inverted 180 degrees through a spiral twist in the rails and then repositioned by another twist section. The trains are also capable of traversing the inside of a 180-degree, vertically-looped track, dumping the loads while in the inverted position. They are returned to an upright position by descending from the top of the loop or going through a twist of 180 degrees.

Cable Drive

The use of a cable or chain to assist rail cars up and down a steep incline appears feasible. This type of system would entail a cable (or chain) and car combination similar to the San Francisco system, except the cable would carry hooks installed at intervals to engage loops on the car frames. This would provide upgrade propulsion and downgrade braking. The use of hooks, in lieu of the wooden shoe used on most municipal passenger-carrying cable cars, provides a more positive means of engagement and reduces the possibility of slippage. The cable drive system could be used in an inclined tunnel segment while using a conventional locomotive system for horizontal haulage. The locomotive used for horizontal propulsion could be uncoupled from the train at the time the first car was engaged by the incline propulsion system, freeing it for the trip up the grade. Power to move the cable is applied through a hoist drum located outside the tunnel. One possible arrangement at the power source and surface dump is shown in Figure 4-5.

Due to the relatively slow speeds obtained and disadvantages in maintenance and operation, cable or chain drive systems are not considered to be practical for long-haul, horizontal transport in tunneling.

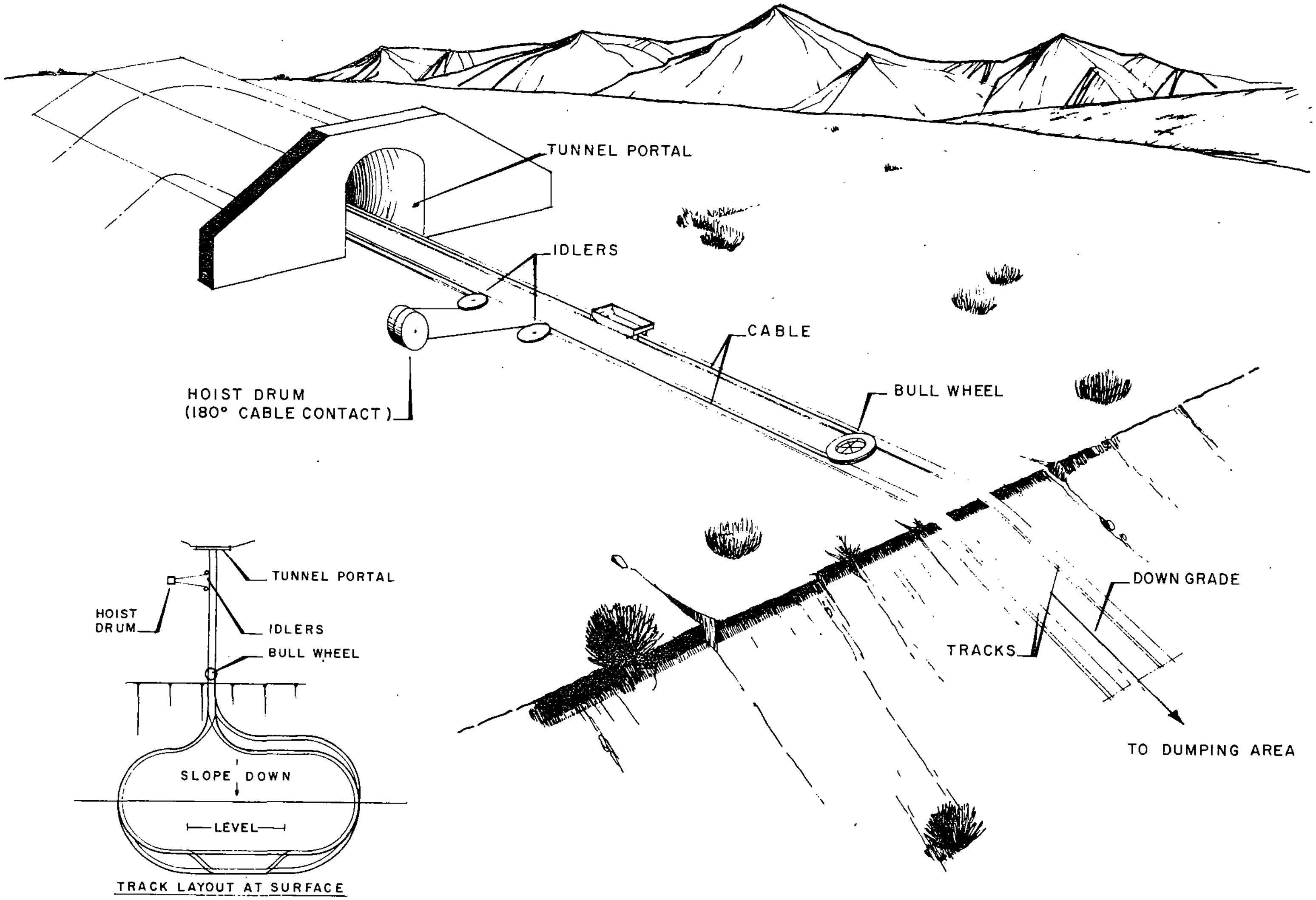


FIGURE 4-5

CABLE DRIVE AT SURFACE DUMP

SIDERAIL SYSTEM

An example of the siderail system concept has been developed* and installed in a mining operation. This concept utilizes individual, electrically-powered transport modules which can be operated separately or in flights traveling on special tracks installed at the sides of the vehicle modules. The modules ride between the tracks which are located close to the horizontal centerline of the modules. The module sizes range up to 3 cubic yards, and each is equipped with a hinged, top-mounted door which is opened and closed by cams at loading and dumping points. The power unit on each module is clutchless and contains dual motors with horsepower ranges from 10 to 30 nominal, and from 43 to 130 maximum. Mounted on the support framing are 2 bus bars which feed 440-volt, 60-cycle a-c power to pickup arms on each module.

The tracks consist of two parallel, standard I-beam sections modified to suit the type of drive under which the modules are operating. The modules run on pneumatic tires with the drive wheels riding the top flange of the I-beam. Contra-wheels contact the lower flange of the I-beam, thus assuring stability. For vertical travel, a toothed rack is attached to the underside of the I-beam. A pinion gear connected to the module drive motor engages the rack, thus furnishing the drive force for the ascent. Thrust wheels which run against the web of the I-beam track provide a constant means of centering the modules between the tracks.

Control is maintained by programming and monitoring system operations from a central control point and includes loading and dumping in transit, as well as operational condition and flight location checks. Control to the modules is through a bus bar mounted on the opposite side of the track from the power bus and through a pickup arm to the module control mechanism.

Figure 4-6 shows a concept of the siderail system in the near face zone, and Figure 2-2 shows typical cross sections for this system installed throughout the length of the tunnel. Muck loading is accomplished by means of an overhead feed conveyor which dumps the material into bins above the two loading guideways. A gantry supports the conveyors bringing muck back to the loading stations. For this system muck must be parceled into loads for module loading at high frequency. The system presented can load six modules simultaneously, once they have been

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*The Dashaveyor system developed by The Dashaveyor Company, Los Angeles, California.

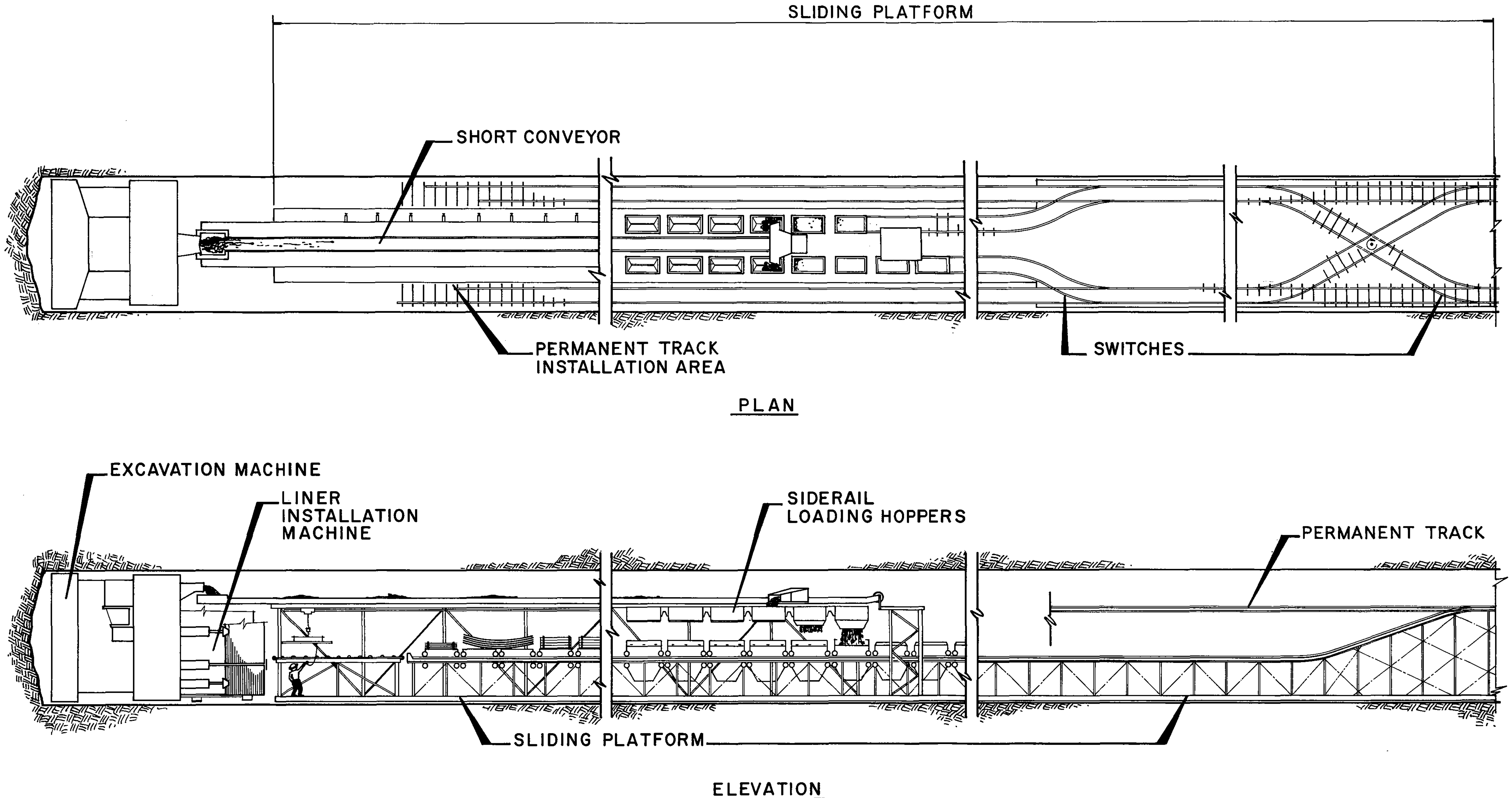

FIGURE 4-6

SIDERAIL SYSTEM
(Near-Face Zone)

spotted under the hoppers. A tripper mounted on the conveyor is provided to alternately fill hoppers on each side of the conveyor. The permanent siderail track is extended in the areas provided along each side of the tunnel and does not interrupt the loading process. A ramp switch allows the modules to climb onto the portable sections of track where they are switched to the desired loading stations. A single guideway extending toward the excavator would permit tunnel support materials to be unloaded ahead of the loading zone, while a guideway cross-over near the trailing edge of the sliding floor would permit access to either of the two permanent guideways from the loading zone. In Figure 4-6, the front end of the loading zone shows incoming materials ready for unloading.

Unloading of muck at a shaft station or outside the tunnel complex would be accomplished either by following a track up and over a loop to dump into a hopper, or by spiraling the tracks in a manner similar to the rifling in a rifle barrel, so that the modules would invert 180 degrees while in horizontal transit.

System Extension

To extend a horizontal system, it would be necessary to utilize a sliding floor similar to that used in the conventional rail concept. The loading operation would be carried out on the center guideways fixed to the sliding floor. These would connect to the permanent guideways by means of ramp switches. The permanent guideways would be located at each sidewall of the tunnel and would be elevated above the floor to permit the movable switch sections to contact them from the underside. Guideway extensions would be installed ahead of the switch points.

Capacity

Siderail system modules are visualized as having as much as 5 tons, or 3 cubic yards, capacity. At the present time, speeds of 50 miles per hour on the horizontal and 4 miles per hour on the vertical can be attained. The cross-sectional area which a single-track system would occupy is about 42 square feet. Figure 2-2 shows this in relationship to tunnels up to 40 feet in diameter. The weight of a loaded module is approximately 7-1/2 tons. The track and support structure weighs about 125 pounds per foot.

Operational Features

A vertical lift application, which requires the use of rack and pinion drive, reduces the speed of the modules to about 4 miles per hour. Thus, there appears to be a limitation on the effectiveness of this type of system when used for both horizontal and vertical runs, because the high speeds attainable on the horizontal cannot be continued on the vertical. Such an application would result in a requirement for a considerable number of units to carry the tonnage on the vertical leg. If the siderail system is used both horizontally and vertically, more power per module is required for rapid vertical lift, i.e., to operate at lift speeds which are necessary to meet system capacity requirements.

State of Development

Present technology has passed the initial research and development stage. A siderail system has been constructed for a copper mining firm at White Pine, Michigan. The system is 5.5 miles long and will carry 10,000 tons of ore in a 16-hour period (625 tons per hour or approximately 0.1 the maximum rate in the rapid tunneling project). It will travel vertically as well as horizontally; but the modules are limited, at present, to a 50-cubic foot (1.8 cubic yards) capacity. It is understood that further research and development is being conducted toward reducing the module weight with respect to payload weight, thus providing larger capacity modules, and toward using one powered module to tow one or more unpowered units.

Technology Limitations

There are definite limitations in the present design of the siderail concept. One is the module size which at the present time is limited to 50 cubic feet; another is the vertical speed limitation of 4 miles per hour obtained under motor overload conditions by the rack and pinion drive. The system can be made applicable to rapid muck transport on a total concept basis. This would include receiving the muck from the excavator, transporting down the tunnel, lifting up the vertical shaft, and running to the dump area on the surface. It should be noted that to successfully handle muck in quantities required for rapid tunnel advance rates, the siderail system would have to be a double-track system.

Advantages -

1. Guideway sections can be racked on the sidewalls of the tunnel, or one on top of the other to conserve floor space.

2. When used for vertical or inclined lift application, the rack and pinion drive provides a positive method of propulsion.

3. Each module contains dual-power units, either of which can individually propel the module.

4. The siderail modular system can be combined with other transport modes by use of suitable transfer methods.

5. The system capacity can be altered by adding to or deleting the required number of modules.

Disadvantages -

1. Power units on individual modules could create a heat problem in the confined spaces of shaft and tunnel.

2. While shaft size requirements for vertical-lift applications are minimal, it is quite probable that other shafts and modes of transport will be required for vertical travel of personnel and construction materials.

MONORAIL SYSTEM

A monorail system has transport modules operating individually or interconnected to form a train. The distinguishing feature is that the modules or cars run on a single-rail track. The cars can be hung below the rail, or can operate on top of the rail by employing stabilizing wheels bearing against the web of the rail. The car-on-top concept has been used in some personnel transport applications where load densities of 300 to 500 pounds per foot of length may be encountered. However, it appears to be impractical for consideration in the bulk material transport application where load densities approaching 4 tons per foot of length might be imposed by an 8- by 8-foot cross-section module and the smallest module section (3 feet by 3 feet) which appears practical would carry approximately 1, 000 pounds per foot of length. Any advantage gained by elevating the transport system to free tunnel floor space could easily be more than offset by problems and cost associated with stability.

The cost of the structural support for the suspended-car monorail, for a given car elevation, is increased since structural members must span the transport system and transmit the load to the floor. The higher the elevation desired, the greater will be the cost of the support structure.

Two approaches are available to attempt to reduce the amount of structural support material required. One is to attach the monorail to the rib sets or liners used for ground support; the other is to hang it from rock bolts in the roof of the tunnel. If ground conditions are such that steel rib sets or reinforced concrete liners are required, additional load-bearing capacity could be designed into the structural members, thus increasing the cost of the ground support system. With the uncertainties that exist in the design of the ground support system, significant benefits should be clearly identified before superimposing problems associated with dynamic vertical, lateral, and thrust loads on the difficult problems of predicting ground forces and transmitting these forces, through blocking and packing, in the same distribution assumed for design of the structural members.

The use of rock bolts to suspend dynamic loads in the range of 50,000 to 100, 000 pounds from the tunnel roof should be thoroughly analyzed and tested before being proposed as a means of supporting the transport system. This approach appears to compound one of the major problems in tunnel construction and might, therefore, be feasible only when working in the most competent rock. Since more than one rock condition may be encountered in any reasonably long segment of tunnel, contractors might be hesitant to depend upon this method even if it proved to be feasible under ideal conditions since any unanticipated ground condition could cause considerable job delay while design solutions were developed.

In either case, support by rib sets or by rock bolts, the conservative approach would be to use structural members for transport system support which are independent of those used for ground support. This would increase the time required for installation of the support structures.

A suspended-car monorail system can be installed to operate as close to the tunnel roof as possible, or so that the cars move just above the tunnel floor. In either case, this system offers the possibility of transporting both inbound and outbound materials although the problem of loading material into the cars would probably be more severe than for conventional rail systems due to the overhead obstructions.

Capacity

Since a monorail system would operate with modular containers suspended from overhead, it is advisable to minimize point loading of the support structure by using smaller containers. The gross weight per module would be considerably less than that of a conventional rail car operating on a track laid on the tunnel floor. If it is assumed that modules with a 4- to 5-ton payload capacity could be used as the material container, from 25 to 30 modules per minute would need to be loaded to handle the maximum advance rate in a 40-foot tunnel. This might be difficult to achieve. One approach to rapid loading using continuous feed from a conveyor is shown in Figure 4-7.

To support a 750-foot-per-day advance in a 10-foot tunnel, it would be necessary to load 5-ton modules at a rate of less than 50 per hour to produce the material flow rate of less than 250 tons per hour. Such a loading rate could probably be attained. If a similar advance rate were to be maintained for a 20-foot tunnel, the material flow rate would be nearly 1,000 tons per hour. This would require a loading rate of 200 modules per hour, or one every 18 seconds. It is possible that if this time could be reduced to about 10 seconds, a mass flow rate of 1,800 tons per hour could be attained. This rate would support an advance of about 750 feet per day in a 30-foot diameter tunnel. A module capacity of 10 tons would, of course, double the system capacity for the same loading rate or reduce the loading rate by one half.

To achieve loading rates of the order of 20 seconds per module for the maximum advance rate in a 40-foot tunnel would require module capacities of the order of 50 tons each. If the empty module weight were 5 tons and the trolley beam and support weight 1 ton over the length of the module, the gross suspended load would be greater than 100,000 pounds for each module.

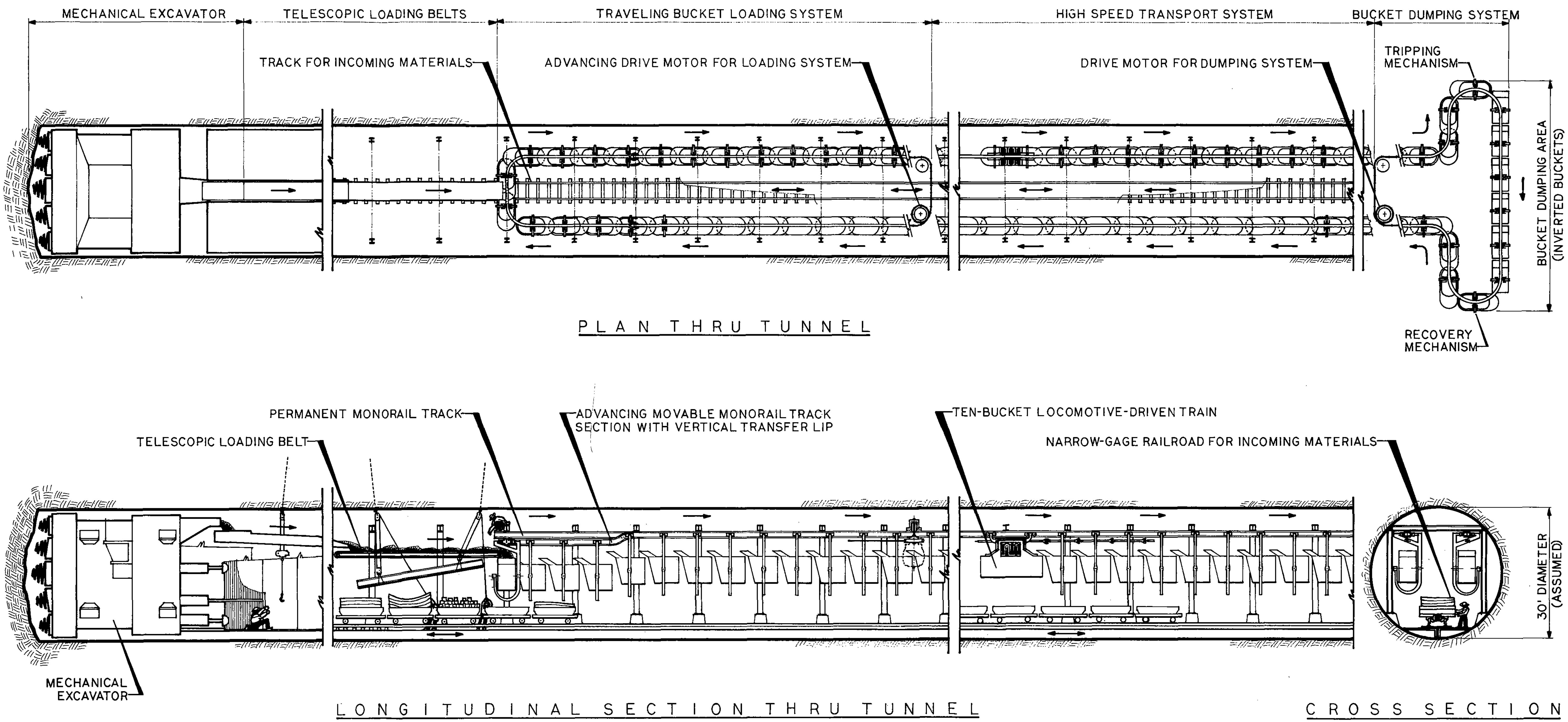

FIGURE 4-7

MONORAIL SYSTEM

In the case of a 750-foot advance in a 30-foot tunnel, if the tunnel distance is assumed to be 5 miles and the speed of the modules 45 miles per hour (or 66 feet per second), 80 modules would be required to transport the load. If the speed were cut to 30 miles per hour, or 44 feet per second, a system of 120 modules would be required to sustain the 1,800-tons-per-hour flow rate. Also, as the tunnel advances either the speed or the number of modules would have to be increased.

Space Requirements

A 5-ton capacity module would have a volumetric capacity of about 3 cubic yards. It would have a dimensional envelope about 4 feet wide by 4 feet high and occupy 5 feet along the line of travel. The suspension linkage and the trolley and trolley beam would add about another 4 feet to the height. One could assume a total envelope about 5 feet wide and 10 feet high, or 50 square feet of cross-sectional area, for a single directional system. Two tracks would be required to handle the material flow which would increase the system cross-sectional area to 100 square feet. Figure 2-2 shows the cross-sectional area required in relationship to tunnels up to 40 feet in diameter.

Operational Features

System speed requirements appear to be within the capabilities of a monorail system. The major constraints would probably be in weight and capacity. An arbitrary limitation cannot be placed on either. However, when a detailed assessment is made of the support structure and suspension mechanism required to safely operate a monorail system containing large capacity (up to 50 tons) load-carrying modules, design limits may then be determined.

There are various methods of module propulsion, any one of which might be feasible for a tunneling operation. They range from individually powered modules to a chain or cable system with a central power source. The chain or cable power method would insure a constant interval between modules and also between flights of modules. Modules could be linked together to form flights (or trains) with the modules at either end providing propulsion capability in either direction. This concept would operate satisfactorily on the horizontal, but modifications would be required for inclined runs. A power assist, involving the chain or cable method, might be required in these instances. This would require each module to be engaged with the chain or cable in both the upward and downward directions. If individually powered modules were used, the rack and pinion drive principle might be considered for inclined movement up a shaft.

A linear induction motor drive for a monorail has been developed in France.* This employs a fixed rotor consisting of a copper sheet inside and along the top of a box-section track. The stator is a spring-loaded subcarriage with four rollers mounted above the load-supporting carriage. Braking action is obtained by reversing the magnetic fields. It is possible that this type of system could be used in an inclined lift as well as a horizontal application.

Loading could be accomplished in a manner similar to that described for conventional rail systems, but may be more difficult due to overhead obstructions. The load-carrying modules could be connected to their suspension arms by trunnions which would facilitate their use with a tipping mechanism for unloading. Modules could also be constructed with bottom hoppers for direct discharge into a surge bin or onto a conveyor belt.

A monorail system might be controlled by an automated programmed control system. However, it would appear that modifications to the signal carrier and pickup mechanisms would be required in order to accomplish the operational objectives.

System Extension

A monorail system would probably be supported from a floor-mounted structure and would consist of twin rails to maintain traffic flow in both directions. As the extension operation would occur in the area adjacent to the loading operation, the two should be free of mutual interference. Interference with installation of the ground support system would also need to be avoided. It is assumed that loading would be accomplished by belt conveyor with the same length and working area requirements as described for railroad systems.

A sliding roof section, supported from the tunnel floor on wheels and containing the loading area sections of trolley rails as well as a double crossover, could be employed to extend the monorail system. This would operate in the same manner as the sliding floor on the railroad system, except that it would be an overhead framework on which the trolley rails are suspended, rather than a steel mat. The sliding rail section as shown in Figure 4-7 would move under the trolley rails which are attached to the fixed-rail support structure. These rails would ramp upward at the trailing edge of the structure to meet the fixed rails. The ramped rails

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*By the Merlin Gerin Company of Grenoble, France.

would be split and tapered inward so that the trolley wheels of the modules could engage the fixed rails on both sides. The trolley wheels would be spring loaded to permit lateral movement when traversing the split-rail sections.

A lateral transfer mechanism, such as presently used in monorail systems but mounted on wheels or skids in order to move with the excavator advance, could be utilized to transfer one or more modules from one trolley beam to the other. Muck loading could be accomplished either before, during, or after the transfer.

Another method of changing the direction of travel would be to install a 180-degree turn section at the end of the rails. This would provide a continuous track for the modules on which they could load and continue their transit to the unloading point. Use of this method would depend on the lateral space and head room available, and would appear impractical except possibly in the largest tunnels.

Advantages -

1. Monorail system remains clear of floor area.

2. With modifications, system can be used on inclines.

3. Carriers other than muck modules can be placed in system to transport tunnel support materials as well as personnel.

Disadvantages -

1. Flow rate difficult to maintain for larger tunnels unless modules are of capacity greater than present practice. Larger capacity modules would require heavier support structures.

2. Might require supplementary system to handle tunnel support materials if extremely high tunnel advance rates were encountered.

3. Loading more difficult than for conventional rail systems.

HOIST SYSTEM

Hoist systems are suitable for material transport only in vertical or inclined lift applications. Skips, buckets, or cages to contain the cargo are generally positioned in a shaft by means of rigid or wire-rope guides. Hoist mechanisms for raising and lowering the skips range from a single drum to a multiple drum type. Power sources can be diesel or gasoline engine or electric motor. Most hoist systems have the hoist located on the surface with the hoist rope feeding over a head frame to the skip in the shaft.

During operation the cargo container reciprocates along a fixed guideway in a cycle of lower, load, raise, unload, and repeat. Since downward and upward travel are along the same guideway, only one container (or smaller containers acting as a unit) can be used per guideway. Thus, the only means of increasing the system capacity is by increasing the speed of travel or increasing the container size.

There are several arrangements for hoists; the most suitable for rapid muck transport from a single level is the balanced or two-skip system. This provides for one skip being at the shaft bottom, loading, while the other one is at the top unloading. The system, along with a man and material cage compartment, can be worked in one large shaft; but in order to keep muck loading and tunnel support material unloading separated at the shaft station in the tunnel, two shafts would probably be used.

Capacity

Current skip hoist capacities are compatible with those required for supporting the muck removal rates in 10- and 20-foot diameter tunnels. They can also handle projected moderate muck flow rates in 30-foot diameter tunnels (up to 500 feet per day advance rate). For example, at the San Manuel Copper Company Mine in Arizona, the skip hoist handles about 1,000 tons per hour. This is done with a balanced-skip arrangement with the payload capacity of each skip being 22-1/2 tons. The depth of the shaft is 2,400 feet, and the rope speed is 2,850 feet per minute. The hoisting machine is rated at 6,000 horsepower. A second installation at San Manuel is underway which will double the capacity.

Needless to say, hoisting systems with greater capacities are needed to accommodate muck removal rates as great as 5,000 tons per hour. Based on the San Manuel speed, skips with a capacity of 150 tons each, operating in a balanced hoisting system at shaft depths ranging from 500 to 3,500 feet, would be capable of sustaining this flow rate. Since it is generally the accepted practice to equate the rope speed in feet per minute to the depth of shaft in feet, the cycle times would be approximately the same regardless of the depth of shaft.

Loading and Unloading

The twin shafts for a balanced-skip system could be located just outside the periphery of the tunnel, one on each side. The tunnel would be enlarged at this point to provide room for the loading and unloading operations which would include the muck transfer equipment as well as storage areas for tunnel support material. Each skip would load from a pocket at the bottom of its respective shaft which would be sufficiently deep to permit muck loading and material offloading to be conducted concurrently.

The skip-bucket configuration for a 150-ton (88 cubic yards) capacity can be visualized as being about 12 feet in diameter and 22 feet in length. The shaft diameter would be from 13 to 15 feet. If the skip contained one or two platforms above the bucket, it might be possible to load prepackaged materials for tunnel support at the surface while the bucket was being emptied. Automatic loading devices would be required which could load and secure a small car on the deck, as well as palletized or containerized materials.

For muck loading, a reversible apron feeder would receive the material from a surge bin and discharge it into a skip. The reversing feature would permit the loading of a skip in either shaft. For unloading at the surface, the skip could be equipped with a tip-over guideway or a bottom discharge gate which would empty the muck into a surge bin for transfer to another transport mode for final disposition.

State of Development

Speeds and capacities of existing installations are compatible with some of the projected needs in the lower ranges of rapid muck removal. However, while advances are being made in hoist capabilities for loads to 22-1/2 ton skip capacity, there is a definite requirement for development of hoisting equipment in capacities of up to 5 times the present capabilities. Such development should also include provisions for rapid assembly and disassembly, as well as ease of moving components from one location to another several miles distant.

In keeping with these requirements, steps should be taken to ensure that drive equipment is made available in the size and capacity ranges needed to maintain the projected high rates of muck removal. These would include motors in excess of 30,000 horsepower and gear reduction units to suit these capabilities.

Advantages

1. Skip hoist systems are adaptable to vertical or inclined shafts and for use in single or double shaft arrangements.

2. Present technology permits hoists to transport material at those rates necessary to handle all required advance rates in 10- and 20-foot diameter tunnels and up to 500 feet per day advance in a 30-foot diameter tunnel.

3. Hoisting equipment would be located at surface, thus keeping the heat source out of the tunnel.

4. As a vertical-lift system, the skip hoist is suitable for use with all types of horizontal transport systems.

Disadvantages

1. System requires transfer equipment link with horizontal types of transport.

2. Present technology will not support projected high average tunnel advance rates (over 500 feet per day in large diameter tunnels).

3. If a large inflow of tunnel support materials is required, it is probable that additional shafts may be required, as double-decked skips in muck shafts may not have sufficient capacity for support materials.

4. Damage to guide ropes could incapacitate hoisting system, and hoisting machine failure would cause system shutdown.

FREE VEHICLES

This category of transport systems is characterized by the use of vehicles or transport modules which have the ability to operate without the use of a guideway. However, to attain speeds greater than 10 to 20 miles per hour, it is often necessary to provide prepared roadways or to use vehicles of special design for the particular terrain.

Free vehicles are usually equipped with rubber-tired wheels, although some operate on continuous steel crawler tracks. A truck is one example of the wheeled vehicle while a bulldozer is representative of the crawler. For the purposes of this study, in which speed of transport is emphasized, the rubber-tired vehicle has been selected over the slower crawler type.

These vehicles are available with either articulated or rigid frames. The hinged joint connecting the forward and rear units is the distinguishing characteristic of articulated vehicles. While the highway tractor-semitrailer combination is a good example of this type of transport, the concern of this study is with the short-coupled type such as used in earth moving projects which can turn in a small radius. In this type of vehicle the forward unit usually contains the power plant (generally a diesel engine) which the operator controls. It is generally mounted on two wheels (although four wheels are sometimes used) which are driven by the engine through a propellor shaft and gearbox. The rear unit, which is usually the cargo carrier, is mounted on two drive wheels. These are connected to the gearbox through a universal-jointed propellor shaft. Some cargo units are equipped with tandem axles for greater wheel load distribution. Rigid frame vehicles operate in the same manner as the articulated type, except that all components are contained in a single, four- or six-wheeled unit. They do not have the shorter turning radius advantage featured by the articulated type due to their rigid frame construction. However, they are comparable in capacity and speed ranges and are more suitable for straight line operation.

Free vehicles can be categorized by their operational characteristics into transloaders and haulers or trucks. The transloaders perform the dual functions of loading and transporting, while trucks can only transport and must be loaded by other mechanisms.

Transloaders

Transloaders pick up material in a scoop bucket and either transfer it to a cargo unit in the transloader for transport or transport it while in the bucket. The larger capacity equipment makes use of the cargo unit concept. Some transloaders are bidirectional in travel, operating equally well in either direction.

Although transloaders appear to be unsuitable for long haul transport, they could serve an essential function in a major tunneling project. When tunnel excavation is initiated from a vertical or steeply inclined shaft, the near face zone activities cannot be performed on a sliding floor until the face moves away from the shaft station a sufficient distance for installation of the sliding floor mechanism. During this period of initial excavation, which may require a distance up to 1/4 mile, transloaders may be the most practical mode of transport between the face and the shaft station. These temporary operations might include discharging the feed conveyor from the excavator directly into the skips and then utilizing a transloader for material transfer as the excavator moves down the tunnel. One loader with a 20-ton bucket operating at an average speed of 15 miles per hour could handle about 600 tons per hour over a 1/4-mile distance, and five loaders could maintain a flow rate of 3,000 tons per hour for the same distance. The relationship between tunnel length, cycle time, and unit capacity for transloaders is shown in Figure 4-8. With equipment at its present state of development, loading can be accomplished in less than half a minute and unloading in about the same time. Maximum vehicle speeds range from about 14 miles per hour fully loaded to 24 miles per hour empty.

From this it can be projected that a 20-ton capacity transloader could load, unload, and travel in both directions between two points 1,000 feet apart in a little less than 3 minutes. This unit could transport about 440 tons per hour for that distance. For a 500-foot run, the cycle time would be about 2 minutes, increasing the material transport rate for the loader unit to about 600 tons per hour. Working closer to the shaft area where the cycle time would be reduced to a little over a minute, a single loader unit could handle about 1,000 tons per hour. Increasing the number of loader units would raise the material flow rate in proportion to the number of units.

At about 1/4 mile for rail systems and somewhat less for continuous systems, the permanent transport system could be put into operation and the need for the transloader eliminated. This temporary transport system would permit the installation of the permanent system and allow it to gradually assume the transport function from the temporary system during

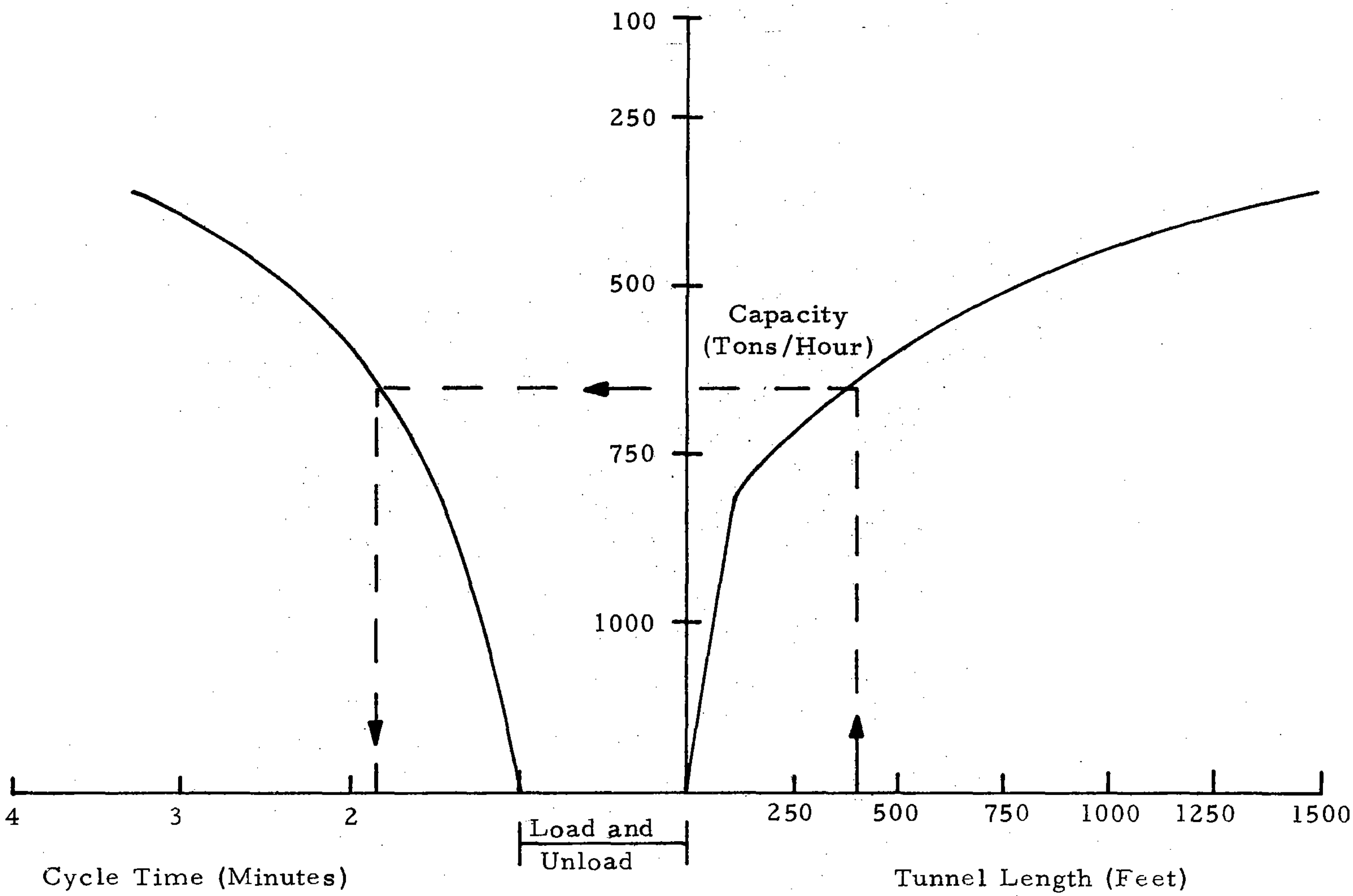


FIGURE 4-8

APPROXIMATE CAPACITIES OF TRANSLOADERS

One Unit = 20-Ton Bucket

the shakedown phase. Other equipment to accomplish the interim muck removal might include portable conveyors, or small trucks if the tunnel diameter permitted.

Since the only apparent application of transloaders in the tunneling project under consideration is for limited use during the initial excavation from a shaft station or for short-haul cross-cutting, this mode of transport is not further evaluated in this study.

Trucks

Hauler trucks may be articulated or rigid frame. Both types are similar in capacities and speeds and can be equipped with various dumping arrangements such as bottom dump gates, side dump, and tilt bodies for rear end dumping. The dumping arrangement for rigid frame trucks is generally the rear end type in which the cargo body is raised at the forward end permitting the load to slide off the rear end.

These vehicles range up to 110 tons in capacity and can attain speeds of about 40 miles per hour on the level. Operation of articulated vehicles is generally in the forward direction, although they have a backing capability for short distances. Such vehicles, if used in tunneling applications, would require redesign both in overall height and width in order to operate within the confined space available for transport. Special designs permitting equally effective operation in either direction would probably be required before these vehicles could be considered for the higher rates of material transport. For some applications, trucks feature a diesel-electric, all-wheel drive which improves their grade climbing capability.

Off-the-road type vehicles can be used to advantage in certain sized tunnels. For example, in a 30-foot diameter tunnel, which is being advanced at 750 feet per day, the muck production rate would be about 2, 200 tons per hour. Assuming the distance to the transfer area to be 10 miles from the face area and 30-ton dump trucks were being used operating at an average speed of 35 miles per hour, a fleet of thirty trucks would be required to support the tunnel advance rate. Similarly, if the advance rate on a 40-foot diameter tunnel were 750 feet per day, with a resulting material flow rate of 3, 200 tons per hour, and the hauling distance were the same, a fleet of thirty 40-ton capacity trucks would be required to handle the material flow.

Truck loading could be accomplished in much the same manner as for conventional rail systems utilizing a sliding floor. This would accommodate the feed belt (and surge bin, if required), as well as a turntable which might be used to quickly reverse the vehicle's direction of travel while being loaded. This would also serve as a means of maintaining transport capability while the roadway was being extended ahead of the sliding floor.

At the shaft station, truck loads could be dumped into ground-level surge bins from which the material could be transferred to another mode of transport for hoisting to the surface. Both the rigid-frame trucks and the articulated haulers have the capability of transporting tunnel support materials and personnel as well as bulk materials although special configurations of the cargo box may be required in some instances.

Roadways - One of the primary requirements for the operation of rubber-tired vehicles at the required speeds is a firm, well-graded roadway. It is imperative that the road be maintained on a continuous basis to support the weights and speeds of haulage equipment necessary to accommodate the projected tunnel advance rates. Roadway width must be sufficient to permit safe, two-way passage of large-capacity vehicles (30 tons or greater) operating at relatively high speeds (30-40 miles per hour). A single-lane road with passing turnouts would not be adequate to maintain the speeds necessary to support the projected material flow rates.

It would be easier to maintain a roadway in a horseshoe or vertical-walled tunnel than in a circular tunnel. In the latter case, the roadbed necessary to permit two-lane operation would require a large amount of fill material. If it were possible to stabilize the muck, it might serve as a base material in a circular tunnel. A top course of gravel and an asphalt surface on top of it could produce an adequate roadway. In a horseshoe or vertical-walled tunnel, this problem would be minimized as the large amounts of fill would not be required.

Life Expectancy - Both equipment manufacturers and operators rate the expected life of a rubber-tired unit at 15,000 operating hours. It is possible that tunnel operating conditions could shorten that to about 12,000 hours. When a rubber-tired vehicle transport system is to be removed and relocated, possibly to another tunnel segment, it is estimated that a minimum of 1 week, three shifts per day, utilizing one man per vehicle would be required.

Technology - At the present time, the large capacity hauling vehicles are capable of handling the material flows which are contemplated. However, to function safely and maintain adequate clearances in a tunnel, they would require redesign to reduce overall width and height. Additionally, development of a capability for climbing steeper grades at reasonable speeds under full load conditions would be a requirement for effective operation where slant shafts were used.

Advantages -

1. Free vehicles with rubber tires do not require a guideway for operation.

2. System capacity can be varied by increasing or decreasing the speed and the number of vehicles.

3. The system can transport both inbound and outbound materials.

4. Units might be guided automatically, thereby eliminating individual operators and increasing vehicle speed.

Disadvantages -

1. Contemporary vehicles occupy an excessive amount of tunnel cross-sectional area.

2. Inability to climb grades in excess of 8 to 12 percent at adequate speeds limits use.

3. Tire wear may be excessive and costly unless roadbed is properly prepared.

4. Operators required for each vehicle under present state of development of control systems.

Other Free Vehicles

Other vehicles which have been developed or are being developed for use without guideways or prepared roadways are all-terrain vehicles and air cushion vehicles or hovercraft.

The development of the all-terrain vehicles has been primarily for military application. However, commercial versions have recently been announced which are suitable for outdoor sports activities.

The drive configurations of the all-terrain vehicles vary from a four-wheel articulated type to a multiple-wheel cargo carrying unit. In addition, half-tracked and full-tracked vehicles are available. Probably the most important features of these vehicles is their ability to travel over rugged terrain at reasonable speeds, as well as to climb relatively steep grades.

The GOER vehicle, developed by the Army, is a good example of a four-wheel, articulated all-terrain cargo carrier. It will transport 8 tons of cargo at a 30-mile-per-hour speed and has the capability to climb a 60 percent slope fully loaded. The vehicle is powered by a diesel engine located in the forward unit. This provides pow r to the front drive wheels through a six-speed power shaft transmission and through a propellor shaft to the rear drive wheels.

Future development of these vehicles may increase their unit haulage capacity and lower the operating and maintenance costs. However, there appears to be little, if any, application in the tunnel complex for all-terrain vehicles in their present form. With increased capacity or for the smaller range of tunnels, they might be suitable for surface transport under conditions of rugged terrain. The features of these vehicles of benefit for in-tunnel haulage could be incorporated in truck designs specialized for the tunneling application; therefore, these vehicles are a form of the truck mode of transport.

Air cushion vehicles for operation without guideways have been investigated for military applications and for commercial personnel transport. For example, a hovercraft capable of travel over land or water is operated for public transport between England and France, carrying people and automobiles across the English Channel. Due to the engine and air noise, excessive dust raised by the supporting air stream, and difficulty in maintaining a precision course in overland travel, these vehicles appear to have no practical application for a tunneling project and are not further considered in this study.

CHAPTER 5

INTEGRATED SYSTEMS

In Chapters 3 and 4 various modes of material transport were discussed and specific examples of basic concepts, which appear to have potential for development into systems with the capability of meeting the material handling requirements for rapid tunneling projects, were selected for further evaluation. The transport modes selected include:

- Conveyors, represented by the troughed-belt concept which appears to be the least expensive, acceptable variation of this mode.
- Hydraulic slurry pipelines, which are reported to provide high capacity, long distance transport of some bulk materials at less cost than conventional surface rail or truck transportation.
- Pneumatic pipelines, which reduce some of the problems, such as system extension, associated with hydraulic systems.
- Locomotive-driven conventional rail systems, which represent the method of transport most frequently used in present-day tunneling practice.
- Sidewheel-driven conventional rail systems, which appear to provide better load distribution and improved application of propulsive force.
- Cable-driven conventional rail systems, which could be used to supplement a locomotive system on steep inclines.
- Siderail systems, which might overcome problems associated with the roadbeds required for conventional rail systems and have the capability to travel vertically.
- Monorail systems, which offer the possibility of removing high volume traffic from the tunnel floor, thus freeing it for other uses.
- Hoists, which are the most frequently used means of vertical lift in present-day practice.
- Trucks, which appear to be the only example of free vehicles suitable for long haul applications in tunneling.

Some of these transport modes, such as pipeline systems, are suitable only for transport of bulk materials, thus requiring another mode of transport for the inbound construction materials. Other modes, such as locomotive systems and trucks, are unsuitable for steep grades; while hoist and cable drive rail systems are applicable only to the lifting portion of the transport path. Due to these and other limitations in the application of the various modes of transport, it is necessary to develop concepts for total systems, consisting of one or more transport modes, which would be capable of transporting both inbound and outbound materials in both the horizontal and vertical (or inclined) segments of the tunnel complex. These total-system concepts provide a basis for comparison of transport modes in relation to the total requirements for material transport. They are not intended to guide future designs without extensive study to establish and verify details.

Relatively large tunnels are pictured, but most of the systems should be adaptable to 10-foot diameter tunnels, where a much more compact configuration may be required. For smaller tunnels using rail systems, double track and sidings may not be required in the near-face zone, which will relax some of the space requirements. The equipment shown is primarily for material handling; showing all other equipment that occupies this space was not practical.

It is most important to visualize the loading and system extension zone as having great length. The reduced length of the systems represented in the sketches can be misleading. The sketches show the loading equipment in the near-face zone to be seven to ten tunnel diameters in length, while the concepts analyzed extend this equipment down the tunnel for much greater distances to facilitate switching long trains and to provide space for unloading cars, laying track, and other essential operations.

The total or integrated system concepts developed include the combinations of transport modes shown in Table 5-1.

In addition to the integrated systems composed of two or more modes, single-mode systems can be considered as total systems if they meet the requirements for transport of inbound and outbound material in both horizontal and vertical (or inclined) attitudes of travel. The side-wheel drive and siderail systems appear to meet these requirements and are therefore evaluated as single-mode integrated systems. These single-mode systems are described in Chapter 4.

Integrated systems can be developed by combining transport modes on the basis of the attitude of travel, that is, one mode for horizontal inflow and outflow and a different mode for upward and downward hoisting. They also can be developed on the basis of type of material or direction of flow, that is, one mode for horizontal and vertical (or inclined) transport of outbound muck and a different mode for inbound materials. Another basis, not so readily apparent, for combining modes could be the characteristics of material flow, that is, one mode used to carry the steady or base-load flow of outbound muck and a different mode used for inbound materials and the variable portion of the muck stream above the base-load quantity.

Selection for Cases 1 and 2 in Table 5-1 is based on the attitude of travel. In all other cases, selection of modes is based on a combination of attitude of travel and type of material. Case 5 could represent the third approach to selection of modes if the muck stream were divided between the outbound hydraulic system to carry the base load and the rail cars, otherwise returning empty after transporting the inbound construction materials. Any integrated system composed of two or more transport modes requires a transfer of material from one mode to another in the shaft station if the basis of selection is the attitude of travel, and increases the congestion in the near-face zone if the basis of selection is the type of material.

The relative space occupied by various combinations of transport modes in tunnels varying in diameter from 10 to 40 feet is shown in Figure 2-2. Concepts for operation at the points of mode interface in the shaft station or near-face zone for the integrated systems listed in Table 5-1 are described in this chapter.

TABLE 5-1

TYPICAL INTEGRATED SYSTEM CONCEPTS

Case	Outbound Material		Inbound Material	
	Horizontal	Lift	Lift	Horizontal
1	Locomotive	Hoist	Hoist	Locomotive
2	Locomotive	Cable Drive	Cable Drive	Locomotive
3	Conveyor	Hoist	Hoist	Locomotive
4	Conveyor	Conveyor	Power Assist	Truck
5	Hydraulic	Hydraulic	Hoist	Locomotive
6	Conveyor	Siderail	Hoist	Locomotive

CONVENTIONAL RAIL/HOIST

One possibility for intermode material transfer in the shaft station for an integrated system using a conventional rail system (driven by a locomotive or side-wheel drive) for horizontal transport of all meterials and a hoist for raising and lowering all materials through a vertical shaft is shown in Figure 5-1.

The muck, transported from the near-face zone in muck cars, is dumped into a track hopper with an apron conveyor in the bottom. The apron conveyor moves the muck to the shaft end of the track hopper and transfers it to a reversible apron feeder which carries it alternately to either shaft and feeds it into a skip or hoist bucket. The hardware used in this concept is within the present state of the art, although some additional development may be necessary to accommodate the quantity rates required by the larger tunnels and higher advance rates.

An excavated width of 55 feet is required to accommodate the twin 15-foot shafts, the track hopper, and the four-track rail complex. The balanced skip hoist system, with double-decked skips, would permit the lowering of supply cars down one shaft concurrently with the raising of muck up the other shaft. The trackage between the shafts would be extended beyond the track hopper a sufficient distance to permit an entire train to unload. The track hopper shown has 750-cubic-yard surge capacity to permit continuous shaft operations in the event of delays in either the horizontal or vertical transport systems.

The number of cars in a train, as well as the size of the cars, will be governed by the tunnel diameter and the rate of face advance. A double-track system with two supply spurs at the shaft station is shown. The track is raised to accommodate the track hopper, and the incline into the tunnel will aid in the deceleration of loaded trains and the acceleration of cars returning to the face. A single-track rail system with passing turnouts can be used for lower capacity horizontal haulage. Skips can be sized to suit the planned muck-removal rate. The apron conveyor and feeder capacities can be regulated by raising or lowering the unit speed.

Flexibility

The ability to handle variable rates of material flow in both directions is due to:

- Varying number of trains and cars
- Utilizing surge capacity in track hopper

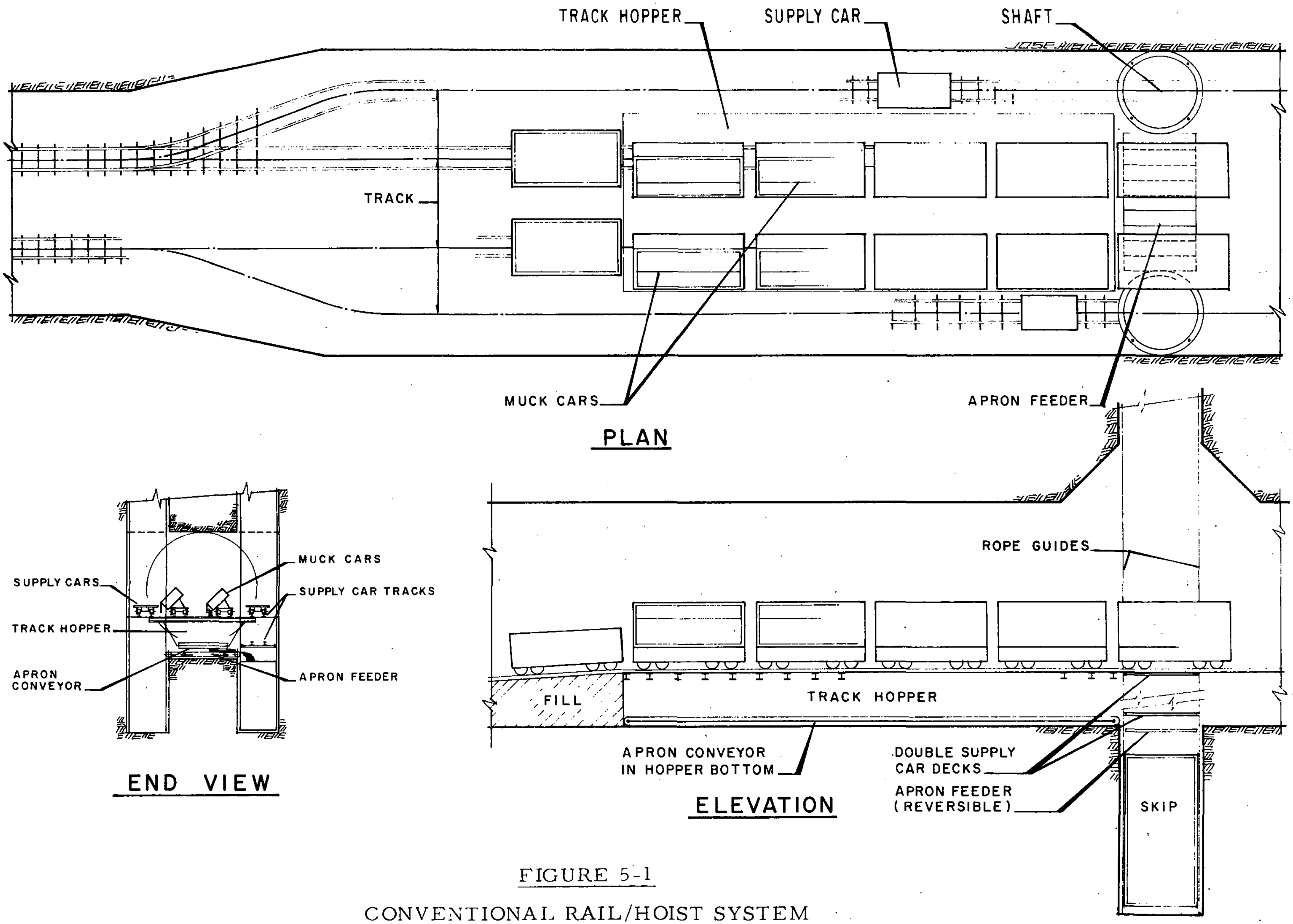


FIGURE 5-1

CONVENTIONAL RAIL/HOIST SYSTEM

- Discharge rates of apron conveyor and feeder can be controlled by varying speeds of units.
- Skip hoist cycle independent of rail haulage due to track hopper surge capacity.

Concurrent Operations

- Material flows alternately in both directions in each shaft.
- Tunnel-support materials can be lowered to tunnel on rail car by means of double-decked skip.
- Construction materials can be hauled to required locations in empty muck cars as well as on special rail cars.

Station Size

Extra length and width of station needed due to:

- Four tracks and track hopper
- Spacing between shafts for dump operations.

Construction Materials

- Size of supply cars restricted by shaft diameter
- Minimum storage area available at shaft station.

LOCOMOTIVE/CABLE DRIVE

The system shown in Figure 5-2 uses conventional rails and rail cars for transporting all materials in both attitudes of travel. It combines locomotive drive for horizontal travel with cable drive for travel in an inclined shaft or tunnel segment, thus eliminating the need to transfer the material from one transporting module to another at the shaft station. Instead, the modules are transferred from the locomotive drive to the cable drive for propulsion on an incline beyond the capability of the locomotive.

In concept, the side-wheel drive conventional rail system could be used in combination with the cable drive in a similar manner. However, the cable drive seems to be less effective for use on the incline than the alternate approach of increasing the number of side-wheel drive units to supply the additional power required. This also raises the possibility of combining the locomotive drive system for horizontal travel with the side-wheel drive for travel in a steeply inclined shaft. The modules could be transferred from locomotive drive to side-wheel drive at the shaft station, or the side-wheel drive could provide supplementary power to the train while being propelled by the locomotive. This principle of supplemental power applied to a transporting module for propulsion on a steep incline could also be used in the case of trucks for horizontal travel combined with cable drive or electric power assist on the incline.

The transfer of the rail cars from the horizontal to the inclined track is accomplished by automatically decoupling the train from the locomotive just short of the base of the incline and then engaging the cars with a hydraulic ram which provides the impetus to start the ascent at a speed matching the cable speed. A continuous chain or cable, with hooks which engage each car at the foot of the incline, provides the power for the ascent up the incline. The hoist-type drive unit for the cable system would be located on the surface, as shown in Figure 4-5.

Trains may be handled continuously or at spaced intervals as the muck flow rate dictates. Empty cars and those containing construction materials are controlled down the incline by the cable. The hook attachments on the cable (or chain) are double-ended so they may engage the cars going in either direction. Aboveground, the system can loop around the dumping area. The track may be graded to provide free rolling between cable pickup points in the dump area.

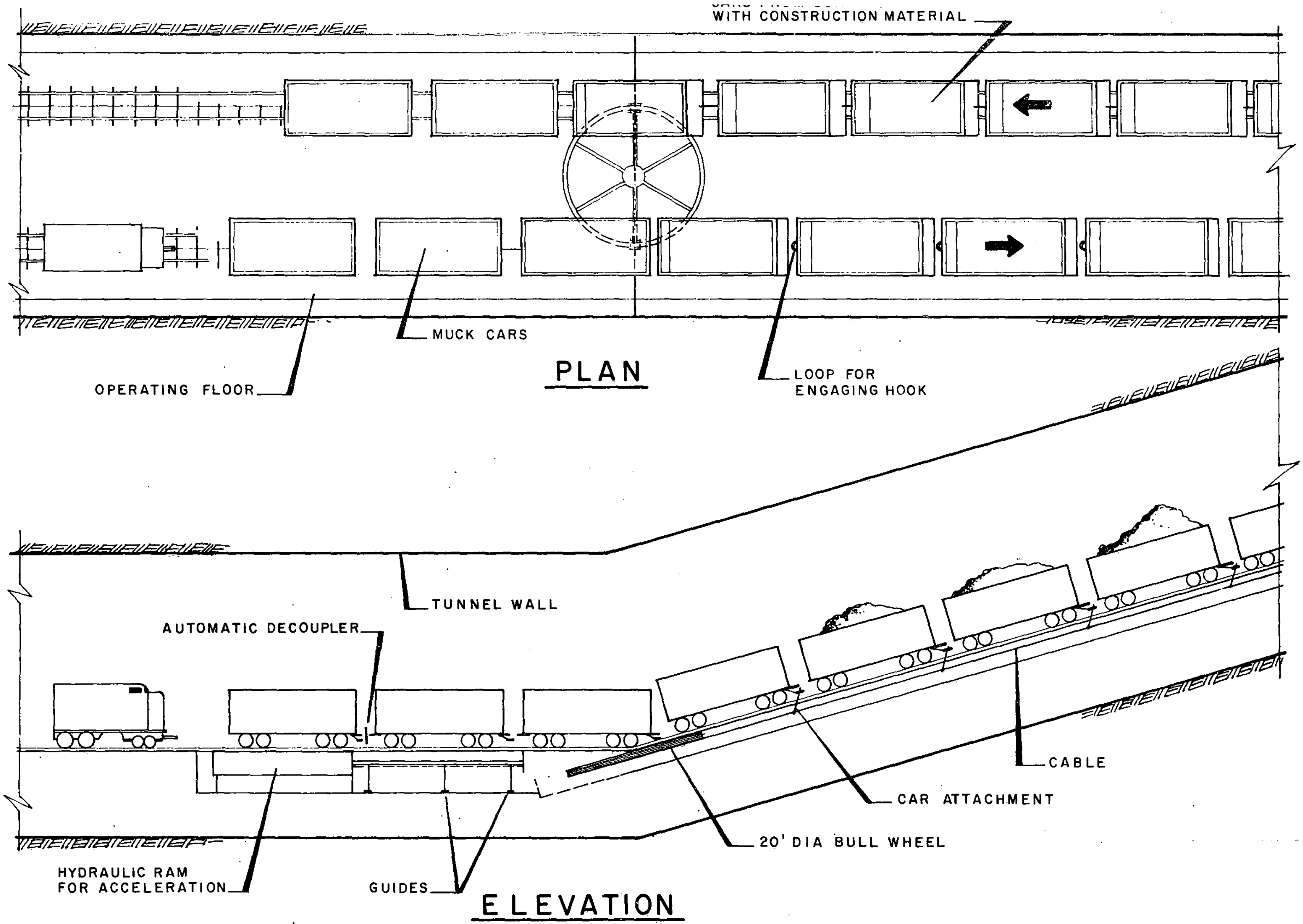


FIGURE 5-2

LOCOMOTIVE/CABLE DRIVE AT INCLINED SHAFT

A control system would be required to provide the proper sequencing of the decoupling, accelerating, and hook-engaging operations. A similar system would be required on the surface to space the trains at the proper intervals for the return trip on the cable.

It appears that the present state of the art in the fields of cable car systems, chain conveyors, and hydraulics is adequate to produce the necessary hardware for this type of system.

Advantages

1. No transfer of material in either direction of travel is required.

2. System capacities can be adjusted to accommodate the rate of face advance by controlling the number of cars and trains as well as the cable feed rate.

3. Muck, personnel, and construction materials may utilize the same transport mode; and in some cases, the construction materials may be placed in the muck cars.

4. The power source for the cable system is located on the surface which removes the heat load and distribution lines from the tunnel.

Disadvantages

1. Not applicable to vertical shafts

2. Difficult to install in small-diameter tunnels

3. Extensive control system required.

CONVEYOR/HOIST/LOCOMOTIVE

Figure 5-3 illustrates a concept for intermode transfer of materials at the shaft station for an integrated system composed of a hoist for raising and lowering all materials, a conveyor for outbound horizontal flow of all or part of the muck, and a locomotive system for inbound horizontal transport of construction materials. If muck transport is divided between the horizontal modes, the outbound rail cars would carry that portion of the muck beyond the capacity of the belt conveyor. Dividing the muck flow between the two modes would avoid the need for complete job shut-down in the event of conveyor failure. As another alternate, a side-wheel drive system could be used rather than a locomotive system. Neither of these alternates would change the basic concept of operations in the shaft station.

The overhead conveyor discharges muck into an elevated surge bin equipped at floor level with a reversible apron feeder. The feeder provides horizontal transfer of the muck alternately to either of the skip or hoist bucket loading stations of the balanced hoist system used for raising the muck to the surface through a vertical shaft. Double-decked skips would provide a means of shuttling loaded supply cars down from the surface and empty cars back up to the surface.

The width of the station is determined by the size of the surge bin which is located between the shafts, thus setting the spacing between them. A 1,000-square-foot material storage area is located between the supply car tracks, and a smaller area beyond the surge bin can be utilized for storage.

The use of a surge bin is required to accommodate the continuous flow of the conveyor and the cyclic operation of the hoist. The reversible feature of the apron feeder permits loading of either skip as required. The overhead conveyor which provides the horizontal transport of muck from the tunnel face to the shaft requires no floor space. The present state of the art of conveyor systems, conventional rail systems, and hoisting systems is believed to be adequate to provide sufficient capacity for muck handling at the projected rates of flow.

Advantages

1. The rates of flow and discharge from one transport mode to another can be controlled by varying the speed of the transport mechanism.

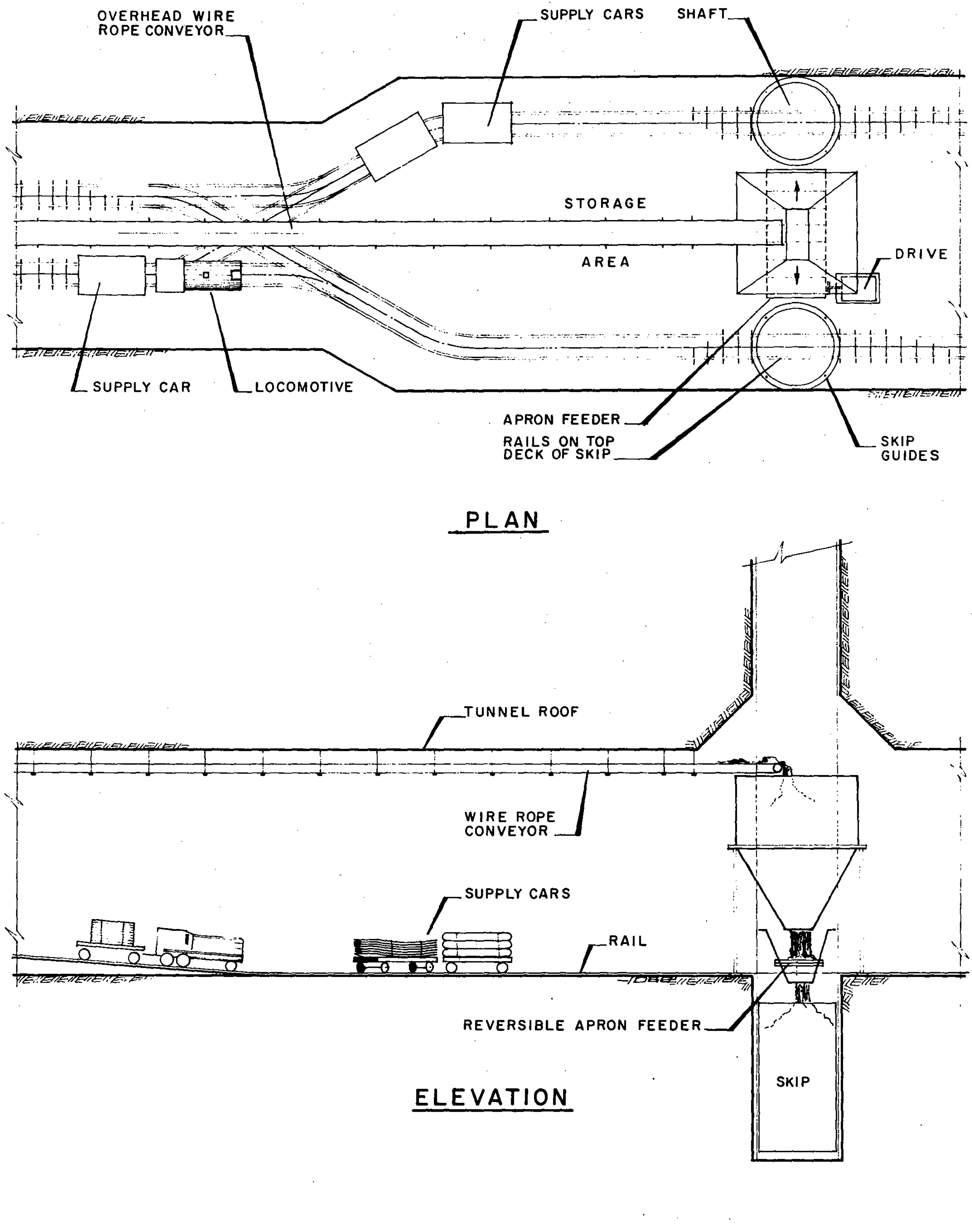


FIGURE 5-3

CONVEYOR/HOIST/LOCOMOTIVE SYSTEM

2. Utilizing the upper area tunnel space for horizontal muck transport provides torage space for other materials near the shafts.

3. Trackage for material hauling is kept to a minimum.

4. The surge bin between horizontal and vertical muck transport modes provides an operational safety factor if delays occur in either mode.

5. Construction materials (packaged) can be moved from the surface to the tunnel in loaded cars on double-decked skips concurrently with the raising of muck to the surface.

6. Muck cars with bottom dumps can be utilized in an emergency to discharge directly into skips.

7. Elevated surge bin affords a minimum shaft depth; if rock conditions required, shaft depth could be kept above the bottom level of the tunnel.

Disadvantages

1. The elevated surge bin occupies valuable cross-sectional area.

2. The surge bin located on shaft centerlines necessitates wide shaft spacing.

3. Track extensions beyond shafts are necessary to move cars on and off skips expeditiously.

4. The size of supply cars and loads is restricted by shaft diameters.

CONVEYOR/TRUCK

The integrated system shown in Figure 5-4 combines a series of roof-hung belt conveyors for hauling muck horizontally and through an inclined shaft, with a fleet of trucks for incoming materials. This concept could also employ the principle of dividing the muck flow between the conveyor and the outbound trucks. Another alternate would be to substitute a conventional rail system with power assist on the incline, in place of the truck fleet.

This concept might show an advantage for smaller (less than 20 feet) diameter tunnels where space is at a premium, if inclined shafts of less than 30 percent can be used. This method of material handling could probably be adapted to larger tunnels. However, a large diameter tunnel (40 feet) with a high rate of advance (750+ feet per day) would require greater quantities of materials and supplies than appears feasible for a rubber-tired vehicle system.

Tunnel construction materials would descend from the surface on rubber-tired, articulated trucks. Several passing turnouts would be required to permit two-way traffic. These would be spaced at optimum intervals for the anticipated amount of traffic. The trucks would combine diesel power with electric drive on the wheels. A trolley for use with a trolley wire on the incline would provide additional power boost upgrade and breaking on the downgrade.

This equipment is well within the present state of the art for the smaller size tunnels although some additional development would probably be required to reduce the physical size of the equipment and provide for bidirectional operation. A limited variance in tunnel advance rates can be accommodated by changing the belt speed, if the belt is sized and powered to handle the maximum flow rate anticipated. It would, however, probably be more economical to use the trucks to handle the occasional peak flow rate of muck rather than oversize the conveyor system.

Advantages

1. Both the muck and construction materials handling systems are flexible in capacities.

2. There is no transfer of either incoming or outgoing materials from one transport mode to another.

3. The overhead conveyor system releases floor space that can be utilized for other purposes.

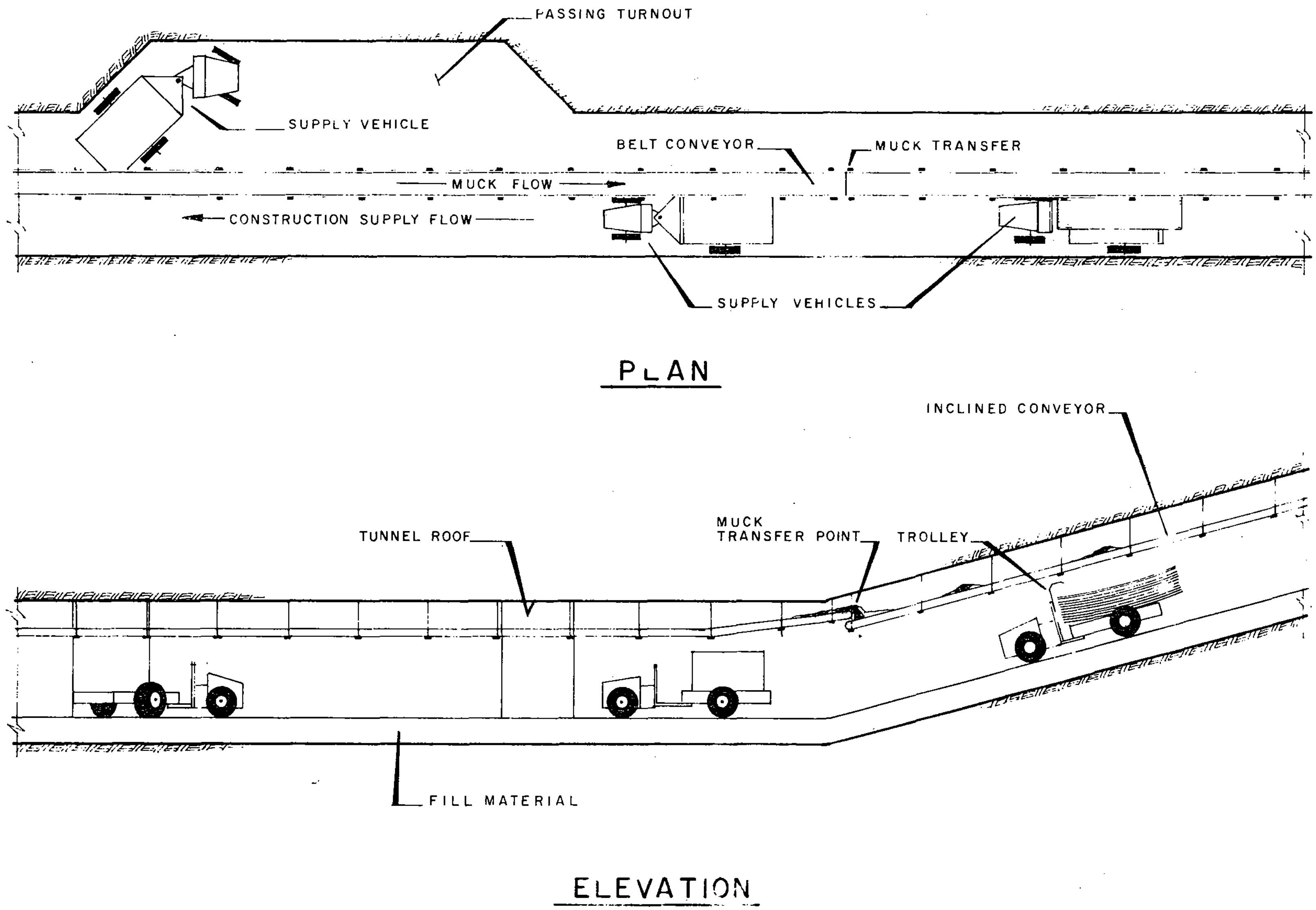


FIGURE 5-4

CONVEYOR/TRUCK SYSTEM

Disadvantages

1. Supply system will require roadbed.

2. Neither transport system adaptable to vertical shafts.

3. Heat and gas release due to power consumption contained in the tunnel.

HYDRAULIC/CONVENTIONAL RAIL

Figures 5-5 and 5-6 show a concept of material handling equipment in the near-face zone for a hydraulic slurry system transporting the normal maximum flow rate of outbound muck, combined with a conventional rail system for the incoming construction materials and the occasional peak load of the outbound muck. Trucks, rather than the conventional rail system, could be used to transport construction materials. If a pneumatic system were substituted in place of the hydraulic system for muck transport, many of the features of the general arrangement would be similar since equipment would be required for injecting the muck into the system and crushing might be required. Problems of system extension, however, appear to be less severe for pneumatic systems than for hydraulic due to the open-end configuration of the pneumatic system.

In the concept shown, a structural frame gantry supports the various equipment required for crushing, slurry preparation, and pipe extension. The use of a sliding floor foundation makes this equipment portable. Crushing may be required in order to insure a pumpable slurry. Various crushers which might be used for this purpose are discussed in Chapter 2. The sketch shows a crusher mounted behind the excavator. A more compact design might combine the crusher into the excavator. Short conveyor sections are shown transporting muck to a mixing chamber where it is combined with the return water. From the mixing tank the muck is transported in slurry form to the pumps (not shown) and pipe extension machinery. The pumps move the slurry up the first sections of pipe. The pipe extension equipment allows pipe segments to be added to both the incoming water and slurry legs of the system without interrupting the flow. Two units are visualized to clamp around the pipe segments and allow flow to enter the pipes before they have been butted together and permanently connected. Before the pipes have been butted together, the second unit moves forward and clamps onto both the section of pipe about to be permanently attached and the next pipe section forward. Flow is simultaneously switched off at one extension machine and on at the second. This process is repeated to "leap frog" the pipe segments down the tunnel without interrupting the flow. A more detailed description of this concept is presented in Chapter 3. Incoming material passes through the gantry via a rail or truck system.

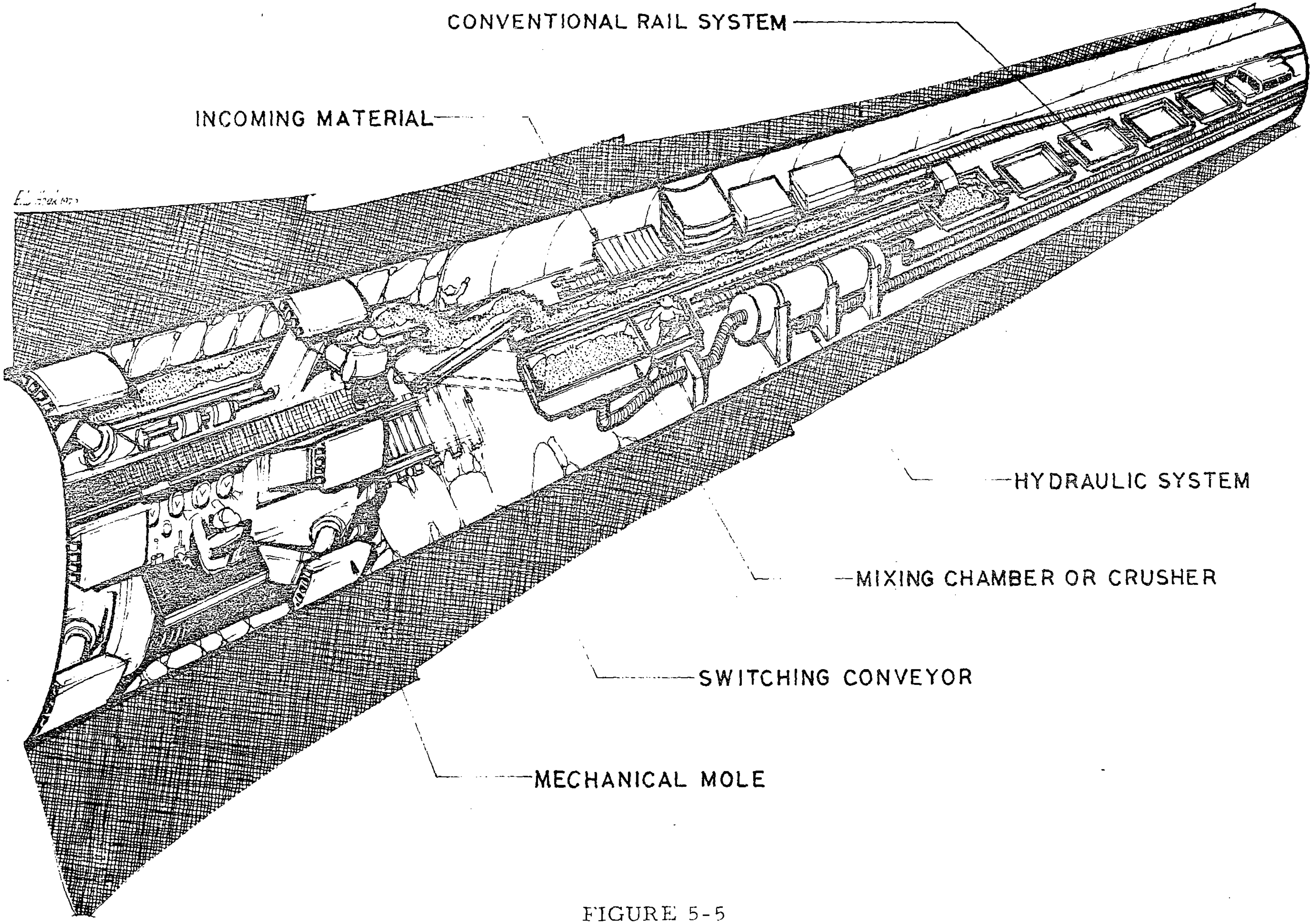


FIGURE 5-5

HYDRAULIC/CONVENTIONAL RAIL SYSTEM
(Perspective)

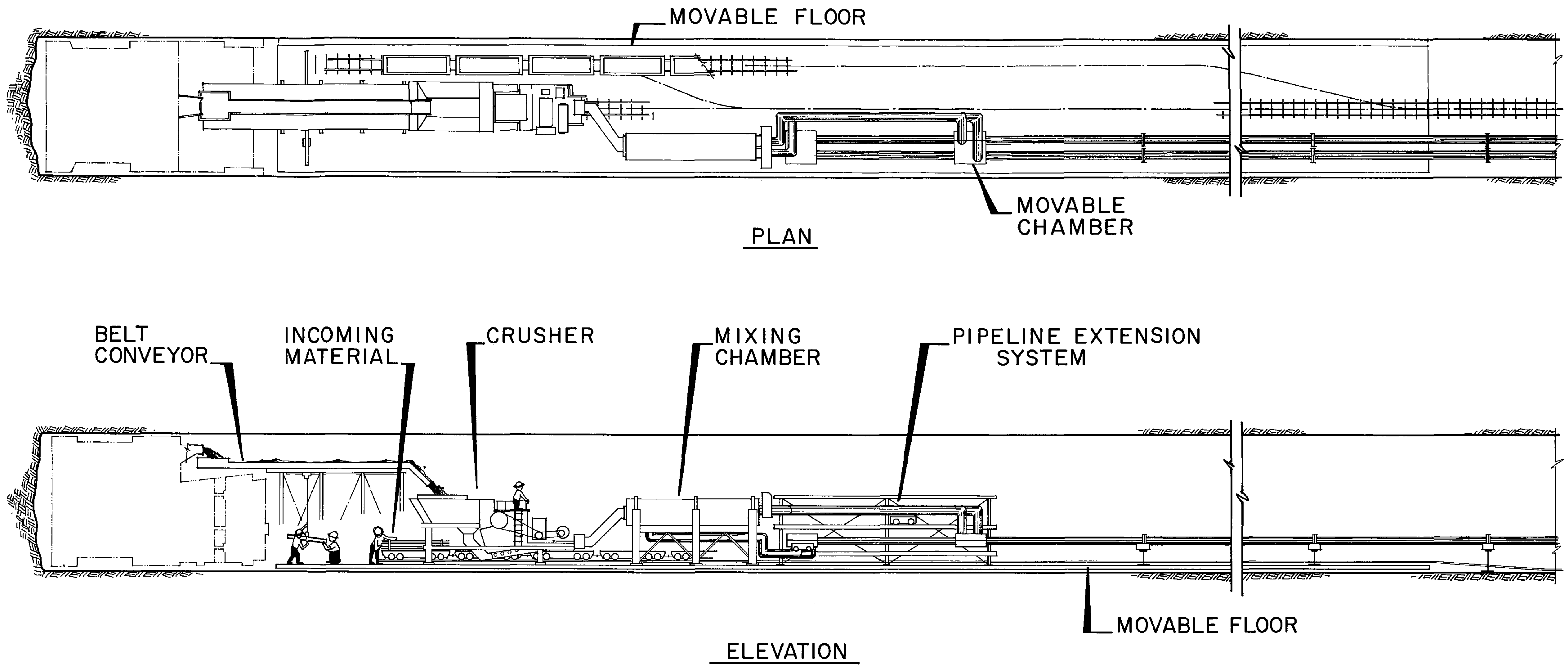


FIGURE 5-6

HYDRAULIC/CONVENTIONAL RAIL SYSTEM
(Near-Face Zone)

To complete an integrated system concept using a combination of hydraulic and conventional rail systems, it is necessary to describe the system operation at the shaft station and for transporting material between the tunnel and the surface. The description of a hydraulic system in these zones is given in Chapter 3. The conventional rail system could interface at the shaft station with a hoist system as shown in Figure 5-1 if a vertical shaft is used, or with a cable-drive system as shown in Figure 5-2 if an inclined shaft is used. A side-wheel drive system could be used through the inclined shaft without transfer of material to another transport mode by providing adequate power through additional side-wheel drive units where needed.

CONVEYOR/SIDERAIL/HOIST/LOCOMOTIVE

The shaft-station operations for a multimode integrated system using conveyor and siderail systems for horizontal and vertical muck transport, respectively, and hoist and locomotive systems for incoming materials is shown in Figure 5-7. Side-wheel drive could be substituted for the locomotive drive and muck could be carried by all systems during their outbound travel to reduce the capacity requirement on the conveyor and siderail systems.

The vertical two-rail, rack and pinion-driven chain of cars used to hoist muck out of the tunnel would be a variation of the siderail system described in Chapter 4. The conveyor used for horizontal muck haulage is similar to that described in Chapter 3 and shown in an integrated system in Figure 5-3.

A nominally sized (250 cubic yards) elevated surge bin with three hoppers handles the muck discharge from the belt conveyor. The hoppers are equipped with automatic discharge gates synchronized with the cars on the vertical lift to permit loading while they are in motion. The surge bin can store sufficient material to cover delays in schedule. The discharge gate controls would be synchronized with those of the vertical transport mode to meet the car spacing and speed.

The vertical rack and pinion drive cars are individually powered by electric motors. The car bodies have covers which are opened at the loading point by means of a dog on the cover contacting a rail in a manner to force the lid open. A reverse-acting rail closes the covers before the vertical ascent is started. A similar arrangement at the surface, shown in Figure 5-8, will open and close the covers at the unloading point. The rate of muck flow will govern the number of cars required for the vertical lift as well as their spacing on the track. The lateral spacing of the muck handling system shafts is dictated by the space required for rapid car loading.

The vertical transport mode is a two-rail arrangement with the cars riding on wheels located along the horizontal centerline and situated at either end of the car. An upper and lower set of wheels contact the upper and underside of the rails, thus insuring stability in any attitude. The rack for the pinion drive is located on the underside of the rails; and when the pinions adjacent to the front wheels of the cars engage the rack, the cars move forward.

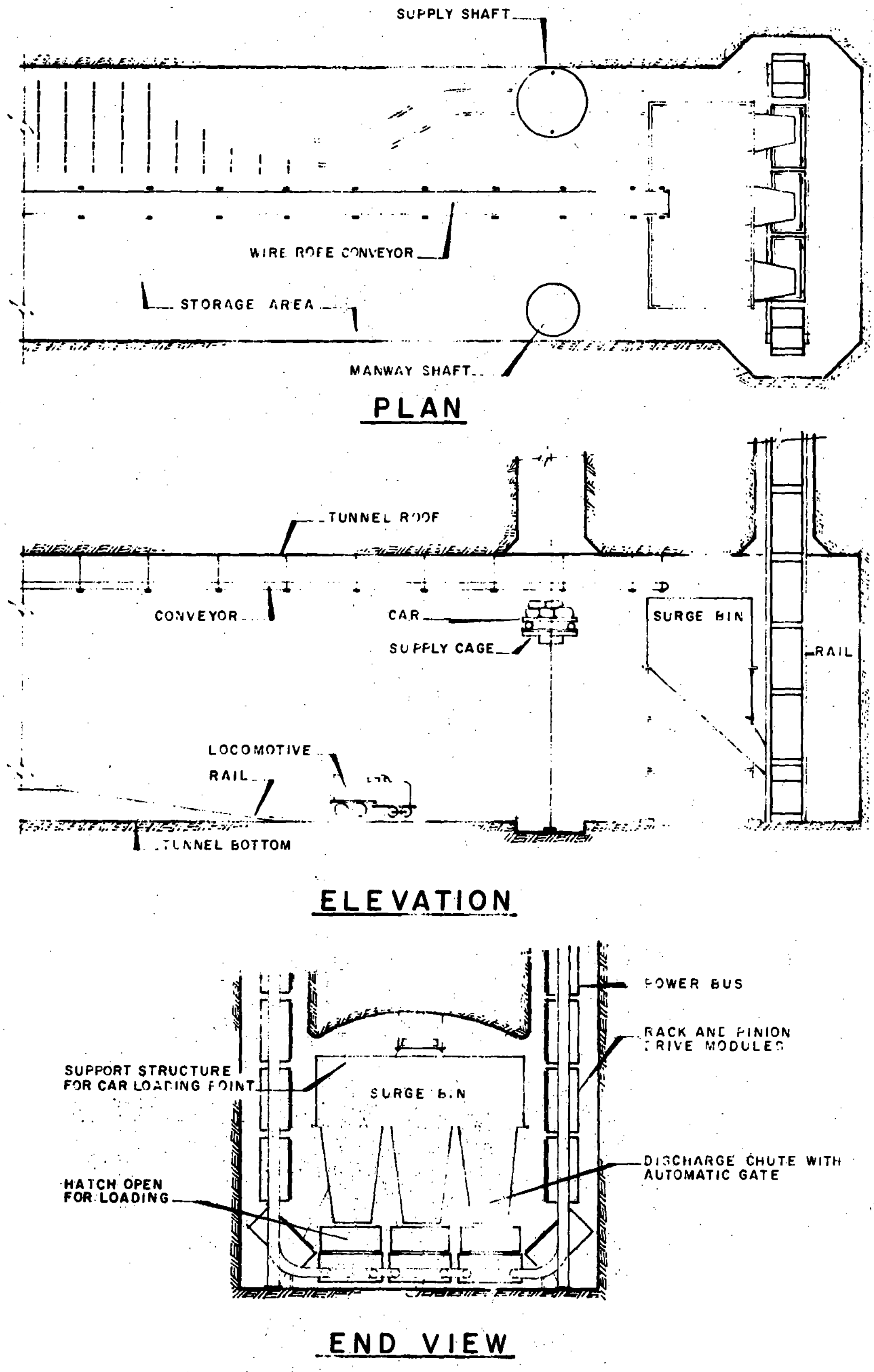


FIGURE 5-7

CONVEYOR/SIDERAIL/HOIST/LOCOMOTIVE

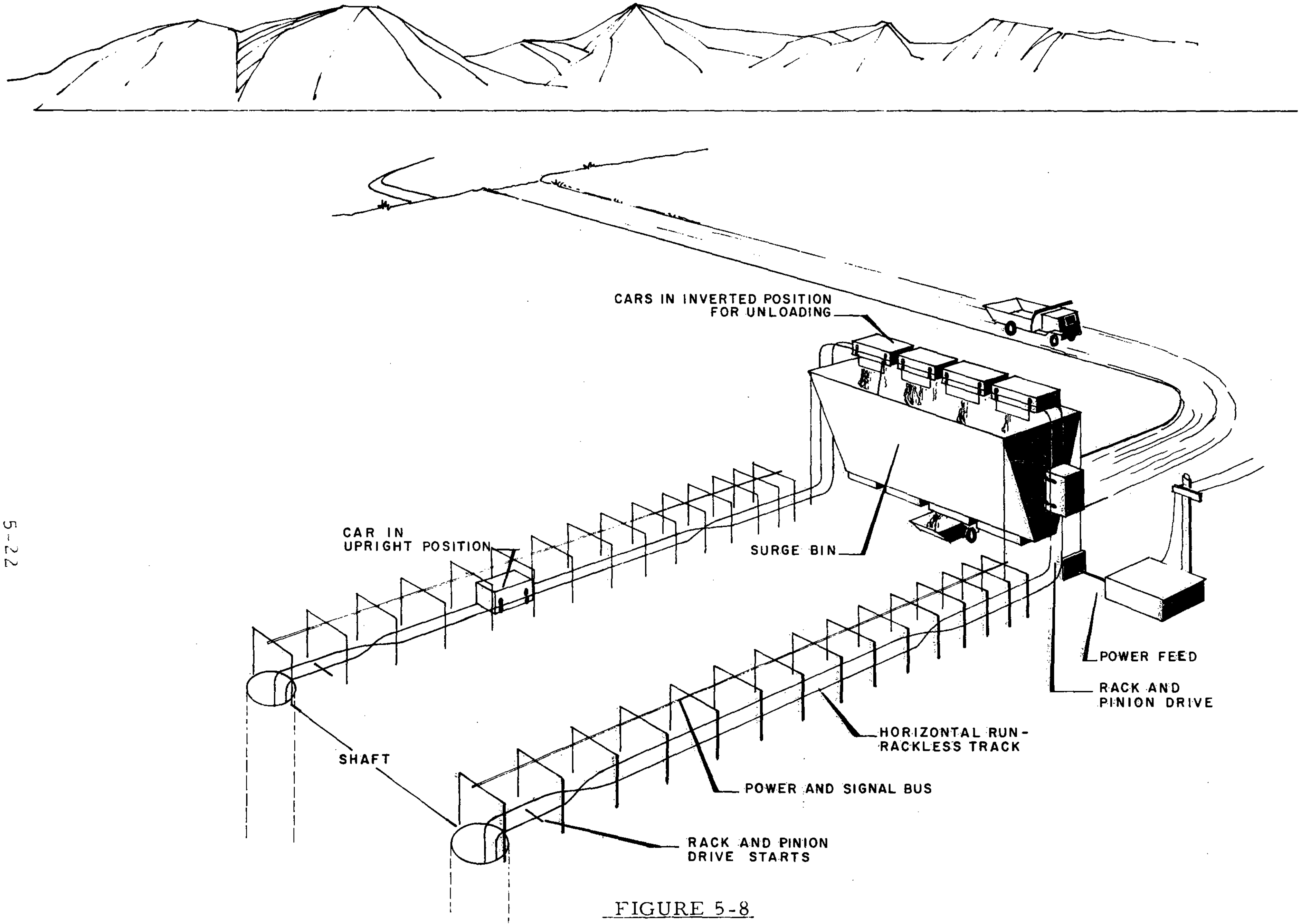


FIGURE 5-8

SIDERAIL/TRUCK SYSTEM AT SURFACE

Since the shafts for the vertical transport system need be only large enough to accommodate the track and cars, it will be necessary to have at least one additional shaft for supply and a manway shaft at the station. Rapid rail transport of these materials from the shaft station to the construction areas is anticipated. This can be accomplished either with a two-track system or a single-track system with turnouts for passing.

Advantages

1. The use of the overhead conveyor for horizontal muck handling conserves valuable tunnel floor space.

2. The rack and pinion vertical handling system provides positive vertical travel in either direction without the use of cables.

3. The capacity of the vertical transport can be increased or decreased by varying the number of cars and their spacing.

4. Each car is equipped with double power units, each of which acting alone can propel the car.

5. The rack and pinion drive is adaptable to both vertical and inclined shafts.

6. The diameter of the shafts required to contain this vertical system is much less than that required for skip hoist operations.

7. The conveyor/siderail system for muck transport separates muck handling from construction material handling.

8. The siderail system is adaptable for vertical use with other horizontal transport modes such as rail or truck.

Disadvantages

1. The present state of the art on rack and pinion drive systems limits the car capacity to about 1.1 cubic yards. Larger units would be required to handle rapid tunnel advance rates.

2. Present vertical speeds of rack and pinion units are about 5.9 feet per second which restricts the capacity of the system.

3. While shaft size requirements for muck transport are minimal, an additional shaft or shafts are needed for transporting construction materials and personnel.

4. Power units on individual cars could create a heat problem in the shafts.

5. An extensive control system would be required to insure a smooth and continuous operation.

PART 2: LOGISTIC REQUIREMENTS

CHAPTER 6

FLOW AND QUANTITY OF MATERIALS

Material handling includes the functions of loading, moving, unloading, packaging, and storing all substances required by or generated in the tunneling process. "Substances" refer to the men, equipment, and materials that are involved in all of the operations. Movement of these substances can be either long-haul transport, such as through the horizontal tunnel; short-haul, such as the transfer of muck from one mode of transport to another; or change in elevation, such as hoisting muck to the surface or lowering construction materials to the tunnel. The term "packaging" refers to the consolidation of a number of units or quantity of a substance for loading onto a transport system. For example, a flatbed rail car may carry several packages of rock bolts to the face. Temporary or intermittent storage occurs in the tunneling process in either a slow-moving queue or as stationary substances waiting to be used or transported. In addition to these material handling functions, any processing (changes in nature or form) of substances required for the material to be compatible with a material handling system must be considered in evaluating the system. These functions of the material handling process are performed continually during the lifetime of the tunnel construction project.

The selection and design of a hardware system to perform the material handling functions requires definition of the material flow characteristics and the quantities and physical properties of the substances to be handled. The flow characteristics and a summary of material quantities is presented in this chapter. More detail regarding the material quantities and physical properties is given in Chapters 7 through 11.

FLOW CHARACTERISTICS

Within the tunnel complex, the flow of materials must follow one or more of the paths established by the tunnel and shaft segments. The configuration of these segments is established by the overall geometry of the tunnel project. For tunnels driven through mountains, all segments will usually be horizontal with grades less than 3 percent. The flow of materials will, therefore, be horizontal in these tunnels. For deep underground tunnels there may be horizontal, vertical, and inclined segments. Shafts may be driven vertically or perhaps on an incline. The flow of materials must follow paths comprised of selected combinations of the horizontal, vertical, and/or inclined segments.

Speed of Material Flow

The speed of material flow is dependent on the characteristics and quantities of materials involved, the types of material handling equipment employed, and the transit distances. For the transport of bulk materials such as muck by continuous types of material handling equipment, the minimum speed of transport can be determined by dividing the volumetric rate of muck production by the cross-sectional area of muck that a material handling system can transport. For example, a 30-foot diameter tunnel driven at 500 feet per day in rock with a 20 percent swell factor will produce 654 cubic yards of muck per hour. A 36-inch wide troughed conveyor can transport a cross-sectional area of about 0.1 square yard. The minimum speed of transport is, therefore, 6,540 yards per hour or 327 feet per minute (3.7 miles per hour). This is the minimum speed of muck removal that must be maintained over the entire transit distance.

For unitized material handling equipment, the speed of material flow over the entire transit distance is usually not constant due to the cycle of loading, acceleration, cruising, deceleration, unloading, and turnaround. Also, the unitized equipment uses some space or headroom between modules which means increased speed to maintain a required flow rate for a fixed cross section of material. Although the cross section of material flow is larger for unitized equipment than for continuous equipment, the maximum speed needed in the transport cycle to maintain the required minimum average speed over the entire cycle may be several times the continuous system speed. For example, if the flow cross section of material in a module is 9 square feet (1 square yard) but the modules occupy only one-tenth of the tunnel length due to head room of nine module lengths between modules, the average speed of the modules would need to be 3.7 miles per hour to remove the 654 cubic yards of muck per hour used in the continuous system example. If the elapsed times required for the various elements of the transport cycle were such that the average speed throughout the cycle is only one-tenth the maximum speed, the modules would need to travel at approximately 40 miles per hour during the cruising portion of the cycle.

The determination of module speed is a cost tradeoff between several factors including

- Number, size, and quality of modules
- Quality of the guideway
- Loading and unloading time
- Acceleration rates
- Degree of automation used.

Flow Constraints

Within the tunnel complex, the movement of muck, men, equipment, and construction materials can be characterized as a two-directional flow of diverse substances. The outbound flow is dominated by the muck removal requirements but is also influenced by the work crews, special equipment, groundwater, and other material movement requirements. The inbound flow is dominated by the ground support and systems extension material requirements, but is influenced by an even wider spectrum of substances than the outbound flow. The combined inflow and outflow determine the materials handling movement requirements.

This flow is constrained by several environmental factors unique to the tunneling process. First, there are only a few routes along which the flow can occur. The alternatives are limited to the number of tunnel-shaft-portal combinations that are available within the tunnel complex. Even outside the tunnel complex, the number of available routes can be limited by the accessibility of public transport facilities, the proximity of urban or suburban complexes, and the availability of sites for storage, aboveground operations, and muck disposal.

Second, the two-directional flow must occur within the confines of the cross-sectional area of the driven tunnel and shaft bore configurations. For the advance rates considered in this study, it is clear that both the inbound and outbound flows will be occurring simultaneously, thus reducing the cross-sectional area available to either inbound or outbound transporting equipment.

The construction activities taking place in the tunnel complex further reduce the area that is available and in addition impose certain safety requirements that must be included in the selection or design of material handling equipment. These safety considerations apply not only to personnel but to equipment as well, since an equipment accident can result in a job shutdown. Almost all portions of the flow are critical in terms of equipment safety because the limited number of routes and the limited cross-sectional area preclude bypassing a breakdown area.

Typical Flow of Materials

A generalized flow of materials for a tunneling project is shown in Figure 6-1. The tunneling operations are listed vertically on the left side of the figure; the zones or physical locations where these operations are performed are listed on the horizontal scale at the top of the figure. The flow of materials is identified for the individual operations, the locations of the operations, and the direction of movement.

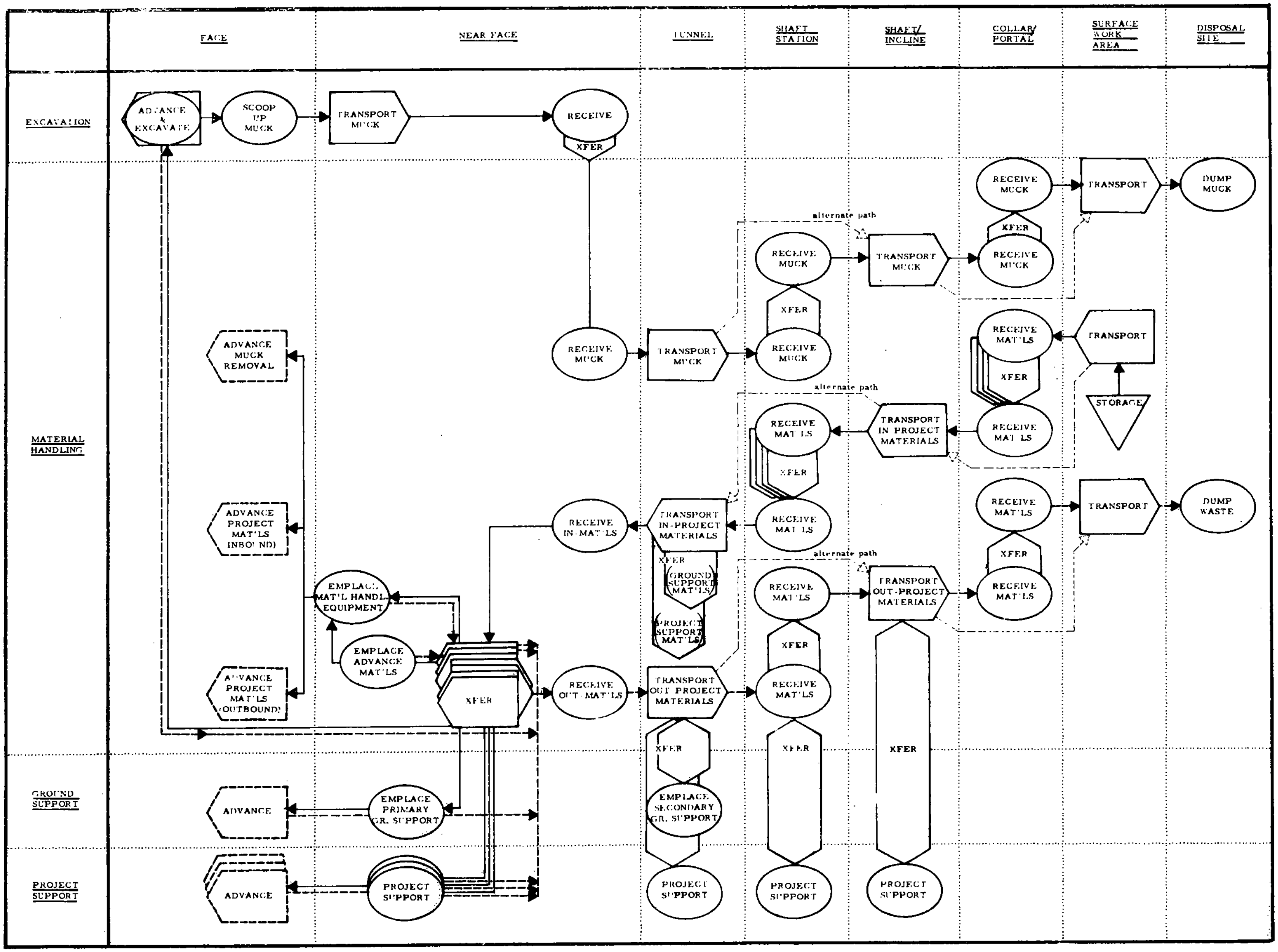


FIGURE 6-1

TYPICAL FLOW OF MATERIALS

Outbound - At the face of the tunnel, the excavation operation penetrates the in-situ material. The resulting muck is scooped up and moved to the rear of the face zone where it is received by the muck-removal portion of the material handling system. The muck is then transported along the horizontal tunnel segment until it reaches the shaft station. At this point, if the same material handling system is used for the vertical or inclined lift, the muck merely changes direction and proceeds up the shaft. For most noncontinuous systems, the muck must be transferred to a vertical or inclined mode of transport. There may be intermediate transfers and temporary storage involved in this operation. After the muck is transported to the collar, another change of direction or transfer may occur; and the muck disposal portion of the material handling system transports the muck to a preselected dump site.

From the tunnel face and from various locations along the horizontal tunnel segment, there is an outbound flow of project support materials. At the end of a shift the excavation, ground support, and other crews must be taken out of the tunnel complex. In addition, wastage including timber and used water, waste concrete, broken equipment, drills or bits, trash, seepage, and other items must be removed. Maintenance and repair crews and equipment may have to be picked up at various points along the horizontal tunnel. All of these items must be transported either partially or wholly out of the tunnel complex. There is also a requirement for picking up and transporting some of these items in the opposite direction towards the tunnel face. While the quantities of return flow materials are not comparatively large, the need for intermittent stop and start points along the horizontal tunnel segment is an important requirement. To accommodate this return flow, an effective material handling system must have the necessary capacity to transport all items away from the face zone and from intermediate points. In addition, the system must be able to stop and start from random locations along the horizontal tunnel segment without interfering with the flow of other materials.

Inbound - At the surface work zone, materials are continually received and stored for use. The inbound flow begins at this point with the transfer of materials from storage or a warehouse to a transport mechanism which moves all items to the collar. These items are transferred to a down-shaft (vertical or inclined) transport system for delivery to the shaft station. There may be one shaft containing one or more vertical or inclined transport systems, or several shafts with separate transport systems. At the shaft station, appropriate transfer equipment may unload the down-shaft transport system(s) and then load the materials onto the inboud horizontal transport system. The inbound system may be the returning horizontal muck removal system or an entirely different system. Most of the inbound materials terminate at the near-face zone.

There are two exceptions: those materials such as roller bits which continue on to the excavation operation; and those items which are needed at various locations along the horizontal tunnel segment for emergency repair and construction, rail or roadbed maintenance, and groundwater removal activities. At the near-face zone, appropriate transfer equipment must offload the incoming materials and move them to the specific location where they are required. Because of the limited available space, these items must be moved in a predetermined sequence to avoid "stacking up" which not only constricts the overall material flow within the near-face zone but hampers the performance of the other operations.

There are several observations regarding Figure 6-1 that are especially noteworthy.

Attitudes of Movement - Regardless of whether the flow is inbound or outbound, it is segmented into horizontal, vertical, or inclined attitudes of movement. The horizontal attitude occurs between the tunnel face and the shaft station. Aboveground movements are usually horizontal or inclined depending on the topography. The vertical attitude occurs between the shaft station and the surface of the tunnel complex. An inclined movement, not shown in the figure, can occur in two places: inclined tunnel segments and inclined shafts. The significance of these different attitudes involves the capability or efficiency of different material handling systems to cope with a given mix of directional requirements. The overall tunnel design including tunnel depth and length, shaft sizes, spacing, and direction (vertical or inclined) results in a sequential combination of movement attitudes through which the muck and construction materials are funneled. Optimization of material handling systems must incorporate this sequence of directions in terms of the relative capability of different or combined material handling equipment to service all attitudes.

Transfer or Short Haul Material Handling - At the near face, shaft station, and collar locations there are a number of transfer functions indicated. The transfer function is a special kind of material handling activity which is essentially a short-haul transport. At the shaft station and collar location it involves the unloading, short-haul, and loading of materials from one transport system to another. At the near face it involves unloading, short-haul, and emplacement of materials or unloading, short-haul, and loading of the materials onto an emplacement device. The transfer mechanism focuses on short distance transport and tends to be specially designed for the particular material to be handled. In current tunneling technology, the "cherry picker" is an example of transfer equipment. The transfer mechanism per se is not examined in this study because it is so functionally related to the specifics of the materials to be transferred.

Congestion - Congestion is a serious problem, particularly in the near-face zone which may extend several hundred feet back of the face. The excavation of muck, emplacement of ground support, provision of project support, and extension of the advancing mechanical systems are all performed in this zone. The equipment and work space envelopes of these operations must fit concurrently within the tunnel confines on a noninterference basis. Within this congested environment, material handling equipment must be strategically placed to remove muck and to bring in the required construction materials at the right time and to the right place.

This situation is schematically presented in Figure 6-2. At the top of the figure, the four basic operations of the tunneling process are shown along with the major materials for each. Below, a plan view of a hypothetical tunneling process is shown in the face and near-face zones. Hypothetical equipment and work space envelopes for the various operations are fitted together into the approximate positions where they are normally located. The materials required for each of these operations are shown coming into the near-face zone; muck and miscellaneous materials that must be removed are shown moving away from the face.

As muck is produced, it is moved to a transfer point back of the excavation operation. There it is loaded onto the muck-removal system. For continuous types of transport systems such as conveyors, the loading involves the transfer of muck from one system to another. For unitized systems, however, an empty module must be available for loading. As soon as one module is loaded, it must be moved to make room for another empty unit. Because of the continuous nature of excavation, it is apparent that there must be a queue of empty muck-removal units waiting to be loaded. In addition, there must be a return flow of empty units from the shaft station to join in the loading queue at the near-face zone.

As new tunnel walls and back are exposed, ground support materials must be emplaced. The distance back of the excavation operation that the ground support operation is performed is dependent on the inherent self-supporting capability of the exposed tunnel. Except in the most competent rock formations, this operation is performed as close to the face as possible. The material transport equipment must be in place to provide the means of bringing forward the ground support materials. This means that systems construction materials and segments of the material handling equipment must be brought forward as well as the ground support materials. This situation is shown in Figure 6-2. The equipment and work envelopes of the ground support and extension operations are shown overlapping, and the material handling system is shown entering these overlapping envelopes. To insure the continuity of sustained operations, the material handling system extension and the other operations must all be space synchronized.

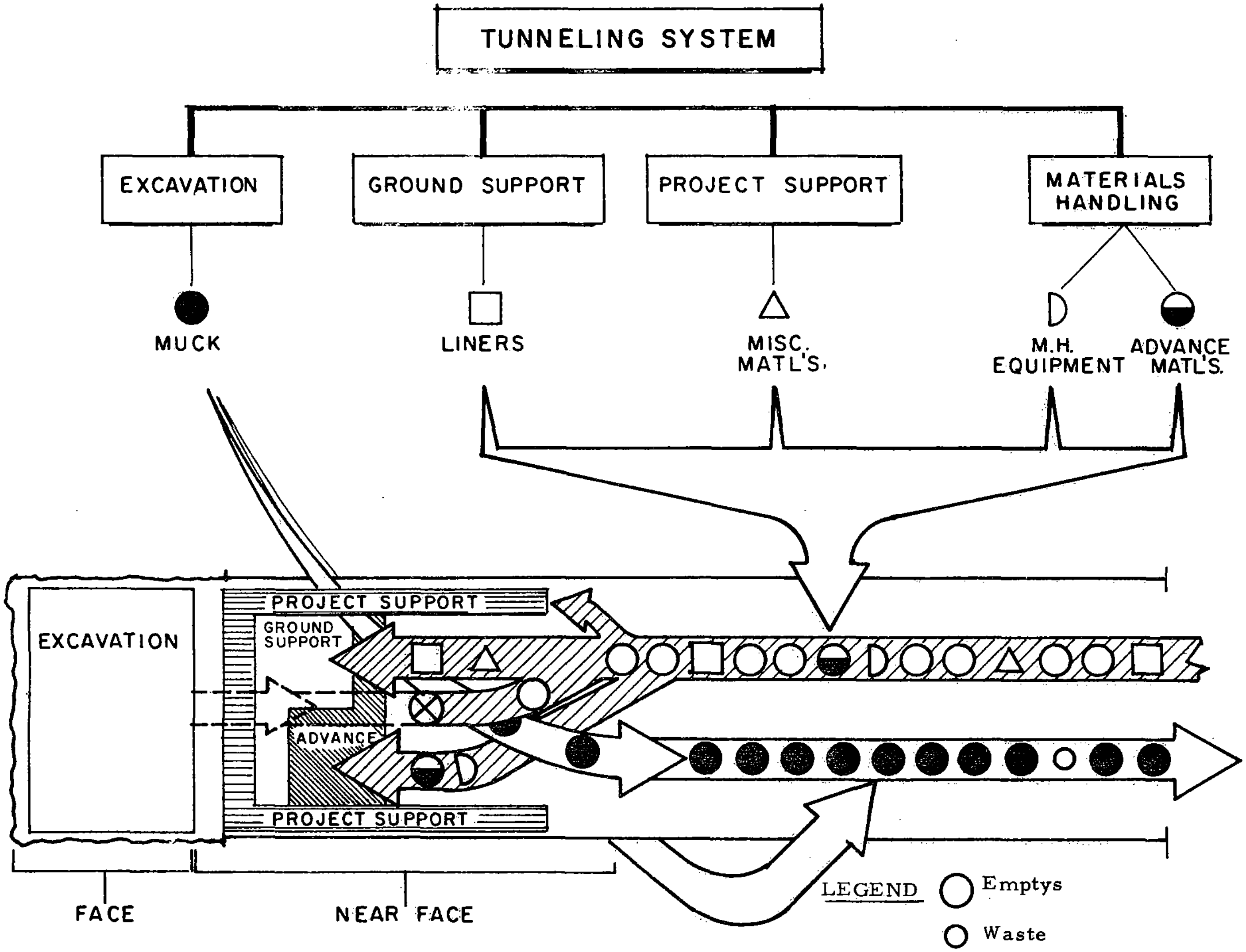


FIGURE 6-2

MATERIAL FLOW IN NEAR-FACE ZONE

Queuing - In Figure 6-2, the flow of materials entering the near-face zone is shown in the form of a queue. The flow is comprised of the various materials required by the operations and includes the returning empty muck-removal modules. These would be replaced for a continuous type of muck-removal system by the returning transport medium such as air, water, or belt. The rate at which these materials are needed at the face is derived from the advance rate and the specific design of the operations. Together they establish the material installation rates which must be maintained. Since there is limited space available in the tunnel for even temporary storage, it is apparent that the flow of all materials must be sequentially programmed for arrival at the face in the proper order of use and at a rate consistent with the material installation rate requirements. This queuing problem is compounded by the fluctuations in advance rate that normally occur in the tunneling process. A mandatory requirement for all material handling systems is therefore an adjustable flow capability which is synchronized with the advance rate.

Transport Loops - In the transport of muck or project materials from one location to another, it is implicit that at the end of the trip, the transport equipment or medium returns to its origin for reuse. In other words, there is a closed transport loop. The overall flow into and out of the tunnel complex is comprised of a number of these internal transport loops. For the muck-removal flow shown in Figure 6-1, different transport equipment could be used for the horizontal flow than for the vertical flow. Each attitude would then have a separate transport loop with possibly different velocity and capacity capabilities. The velocity and capacity of each loop must be integrated with the other in order to insure an overall material handling system capability which is compatible with the material flow requirements of the tunneling process.

Another type of transport loop is that formed by temporary use materials such as forms for placement of concrete or temporary ground support materials. These materials are set in position for use in the near face zone, but after the face and near face zones have advanced away from this point of use the materials are removed and moved forward to the new location of the near face zone for reuse. This produces a continuous loop flow of material entirely within the tunnel and near face zones. The material transport system must have the capability to accommodate this internal loop flow of material simultaneously with the flow of inbound and outbound material.

Variations In Material Flow

The material flow requirements are continuously changing for two basic reasons. First, the actual advance rate of a tunnel face will change from day to day depending on the rock conditions encountered, equipment down-time, and overall capability to maintain continuous operations. For a given average advance rate, a material handling system must have the capability of supporting a range of advance rates including peak rates as much as 100 percent greater than the average. Second, as the face is continuously advanced, the length of the horizontal tunnel is constantly extended. The overall length of the material handling system is, therefore, constantly increasing causing an upset in the velocity-capacity relationship of the transport system. To respond to this, a material handling system must have the capability of constantly adjusting to the changing flow requirements imposed by this increased transit distance. The manner in which a material handling system adjusts is dependent on the type of equipment used.

For continuous systems, the transit velocity is nearly constant. As the tunnel length is increased, the continuous system is extended by installing additional equipment segments. The addition of these segments does not change the overall transit velocity. For surges in the muck production rate, the continuous system can respond in two ways; by increasing its transit velocity, or by loading the system more heavily. If excess capacity in the form of reserve velocity or ability to accept more material at constant velocity is designed into the system, the system is operated at less than its capacity most of the time, thus not obtaining maximum use of the investment.

The velocity of unitized systems is not constant over the entire transit distance. Each module must be loaded, accelerated to cruise speed, decelerated, unloaded, and sometimes turned around. The times required for each of these activities can be combined into a single parameter, the system cycle time. This cycle time must be compatible with the muck removal and project materials movement requirements. As the tunnel length is extended and for surges in the muck production rate (and thus surges in the necessary construction rate), the unitized system can respond in two ways. First, the cruise speed of the modules can be increased to maintain the required cycle time. Second, for a fixed or maximum cruise speed, more modules can be added to the system, thus increasing its capacity. Response could also be accomplished by substituting larger capacity modules if physically possible.

The addition of more, or larger, modules is feasible only if they can be absorbed by the material handling system without upsetting the material flow or exceeding the loading and unloading capabilities of the system.

This variation in material flow rate is illustrated in Figure 6-3, which also draws attention to the possibility of combining a continuous system operating steadily at full design capacity to meet the base-load muck requirement with a more flexible unitized system to transport the incoming materials and the variable portion of the muck requirement. Since the unitized system is already required to handle incoming materials, only minor modifications of the unitized system would be necessary to handle the peak load muck transport.

TYPES OF MATERIALS

The substances involved in the tunneling process depend on the specific design of the operations. The use of hydraulic jets for rock shattering in the excavation operation, for example, would require a different set of men, materials, and equipment than those required for conventional (cyclic) excavation.

Material Characteristics

From a material handling standpoint, the important characteristics of the materials to be moved are dependent on the type of material handling equipment considered. The abrasiveness and maximum lump size of muck are important factors in belt conveyor design but are of less importance in rail car design. In general, however, an important material characteristic is whether it is a discrete or bulk commodity. Discrete materials have fixed dimensions, shapes, and weights, while bulk materials do not.

For discrete materials, the important material handling characteristics are the size of each unit of material and the packageability of the units. Size refers to the combined dimensions, shape, and weight of a unit. Packageability is the ability of the units to be consolidated for collective loading onto transport systems. These characteristics are important because they are used along with material quantity data to evaluate material handling equipment in terms of weight requirements, power requirements, capacity requirements, and loading requirements.

For bulk materials, the important material characteristics include the material density, maximum lump size, material temperature, wetness, abrasiveness, and chemical activity properties. The material density is important in the sizing of the material handling equipment and in the determination of power requirements. The material temperature may influence the selection of materials used in the construction of material handling equipment. Wet materials can be sticky or have properties

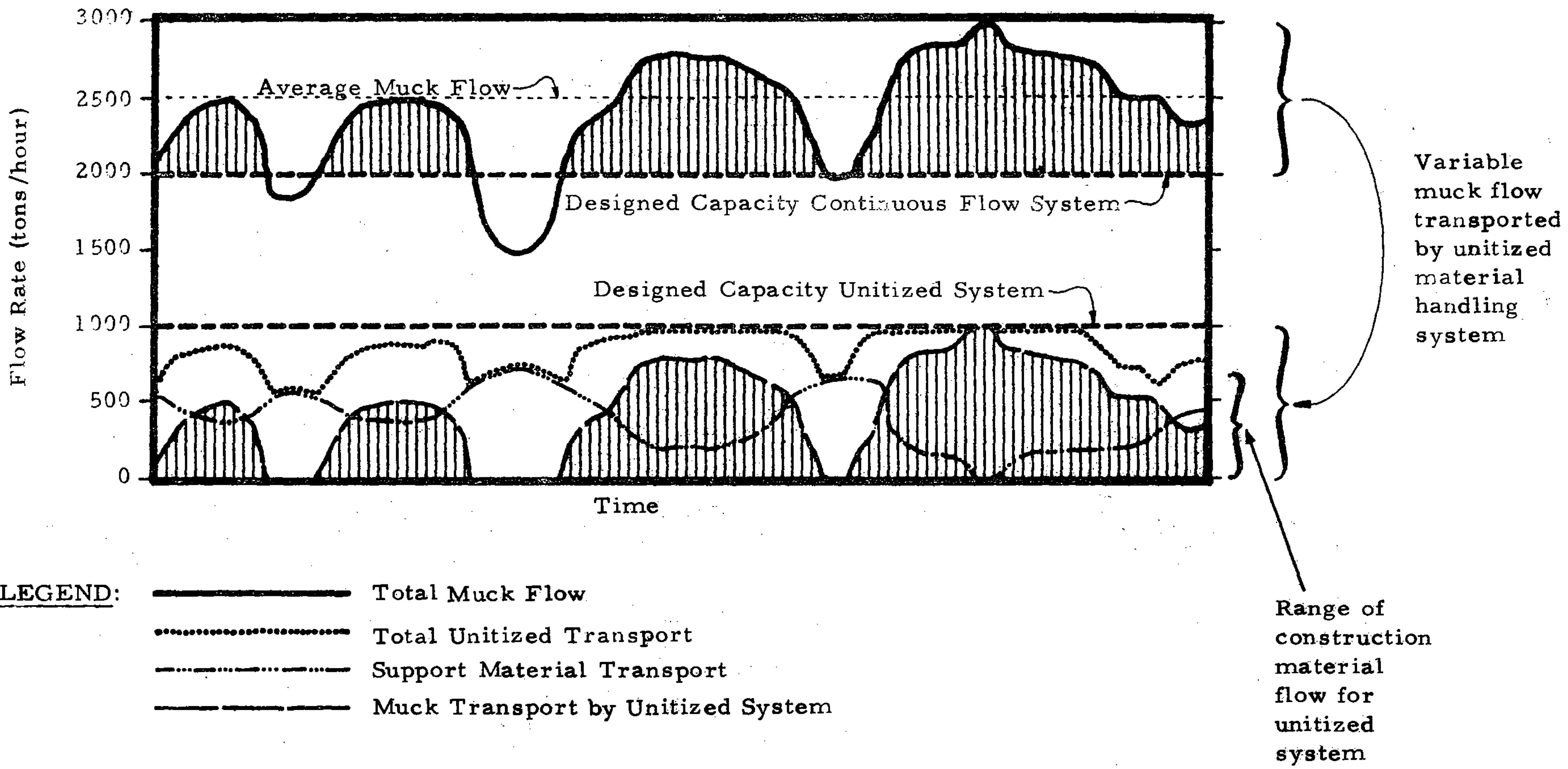


FIGURE 6-3

VARIATIONS IN MATERIAL FLOW RATES

approaching liquids and impose special material handling design requirements. Abrasiveness and chemical activity may influence the durability and maintainability of material handling equipment by causing excessive wear and corrosion.

Quantities of Materials

The quantity of materials generated and required in the tunneling process is more meaningfully expressed in terms of quantity rates which incorporate the dynamic aspects of tunneling. These quantity rates are dependent on the rock conditions encountered, the tunnel geometry, the achieved advance rate, and the specific design of the tunnel system. The geometry and face advance per unit time essentially define three-dimensional, cylinder-like space whose periphery must be supported. In addition, all operations must be advanced the length of the cylinder in pace with the face advance. The specific design of the tunnel operations establishes the types of materials needed for project support, construction, and advance within the three-dimensional figure.

Muck - The major material generated is muck, and its rate of production is based on the bore configuration being driven and the advance rate. The bore configuration is a preselected tunnel design feature which establishes the cross-sectional area to be driven. The length of tunnel driven in a period of time multiplied by the cross-sectional area determines the volume rate of material to be excavated. The advance rate is established by the rock penetration method used, operating speeds, and the varying rock conditions encountered. For varying degrees of rock formation hardness and stability, the rock penetration equipment for a given operating speed will produce various quantities of muck. The muck removal requirements for various advance rates and circular tunnel diameters have been determined and are shown in Table 6-1. For a given tunnel diameter, increases in the advance rate result in linear increases in the muck-removal requirements. For a given advance rate, increases in the tunnel diameter result in a second power function increase in the muck-removal requirements. If the bore configuration is changed from circular to vertical sidewall for the same diameter, the quantity rates shown should be increased by a factor of 1.1 . All of the quantity rates shown are far in excess of what is currently produced by the best sustained advance rate achieved to date, which is reported to be 228 feet per day for a one-month periond.

Figure 6-4 presents data for all muck quantity rates, in terms of tons per hour and cubic yards per hour, produced by advance rates from 10 to 2000 feet per 24-hour day in tunnels with circular or vertical sidewall bores of 10 to 40 feet in diameter.

TABLE 6-1

QUANTITIES OF MUCK

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)							
	10		20		30		40	
	Cubic Yards per Hour	Tons per Hour	Cubic Yards per Hour	Tons per Hour	Cubic Yards per Hour	Tons per Hour	Cubic Yards per Hour	Tons per Hour
300	44	95	175	382	393	860	698	1,529
500	73	158	292	637	655	1,433	1,163	2,548
750	110	238	438	955	983	2,150	1,745	3,823
1,500	220	475	875	1,910	1,965	4,300	3,490	7,645

NOTES

1. Advance rate is for 24-hour day.
2. Bore configuration is circular.
3. Specific gravity of in-situ material is 2.6.
4. Swell factor is 20 percent.

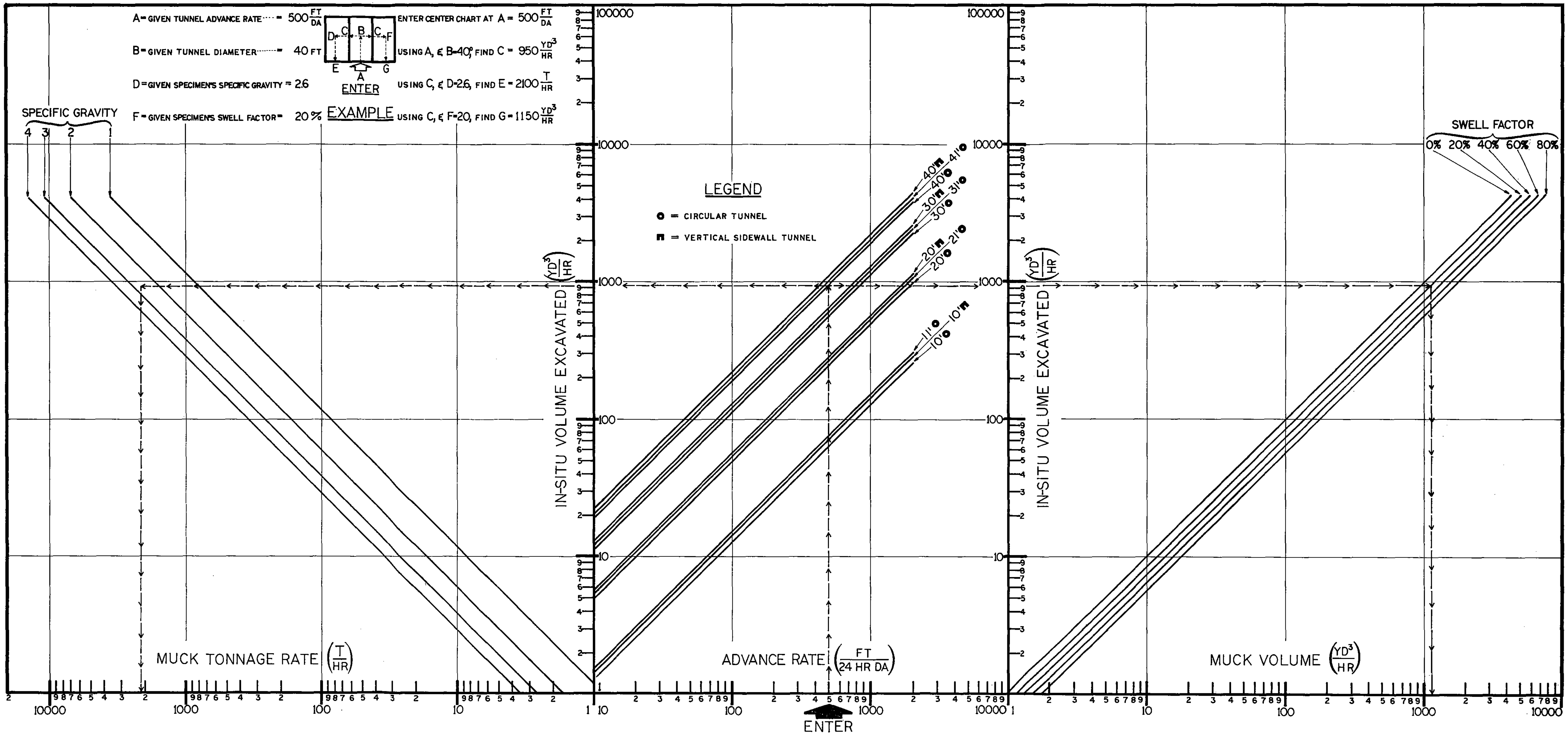


FIGURE 6-4

MUCK QUANTITIES

Ground Support - The quantity rates of ground support materials are a function of the exposure rate of new tunnel walls and the ground support technique employed. As the face is advanced, ground support materials must be emplaced about the bore configuration of the exposed tunnel walls at a rate which ensures adequate structural support for the advancing tunnel. There are currently four basic techniques of ground support: shotcrete, continuous liners, ribs, and rock bolts. Each of these has specific materials which are peculiar to that technique. There are, however, optional design features and material substitutions possible with each. The following ground support material quantity rates are based on design features which are estimated to be typical.

Figure 6-5 gives data for quantity rates of bulk ground support materials such as shotcrete or continuous liners which form a continuous cover over the exposed tunnel wall.

Shotcrete - The number of shotcrete cybic yards per hour and tons per hour, obtained from Figure 6-5, to support the various advance rates and tunnel diameters are shown in Table 6-2. The assumed design features, that is, shotcrete density and thickness, are merely estimates and are not the result of design calculations. A comparison of the muck removal tons per hour with the shotcrete tons per hour shows a ratio of about 10:1 except for the 10-foot diameter tunnel where it goes down to 6:1. The implication here is that the input of shotcrete alone will represent 10 to 16 percent of the muck that must be taken out. The reason for the high percentage is due to the thickness and thus weight of shotcrete around the bore periphery which is approximately 10 percent of the cross-sectional area.

From a materials handling standpoint, these mass and volume rates do not pose insurmountable transport problems even for today's material handling capabilities. In actual practice, however, the characteristics of concrete combined with the large volume rates constitute a most difficult materials handling task. The constituents, as well as the concrete mixture itself, are bulk commodities which are amenable to most transport methods. It makes a great deal of difference, however, whether the constituents are mixed at the collar or shaft station and then transported to the face, or whether the constituents are transported to the face and then mixed. In the former case, special equipment and attention is required to ensure that the mixture is ready for immediate emplacement upon arrival at the face. Delays or breakdowns in mixture transport can result in premature setting which can impair or destroy the transport equipment and also cause considerable delays in the whole tunneling process. In the latter case, the receipt and mixture of the constituents requires space-taking equipment which imposes further space constraints on the available working area in the near-face zone.

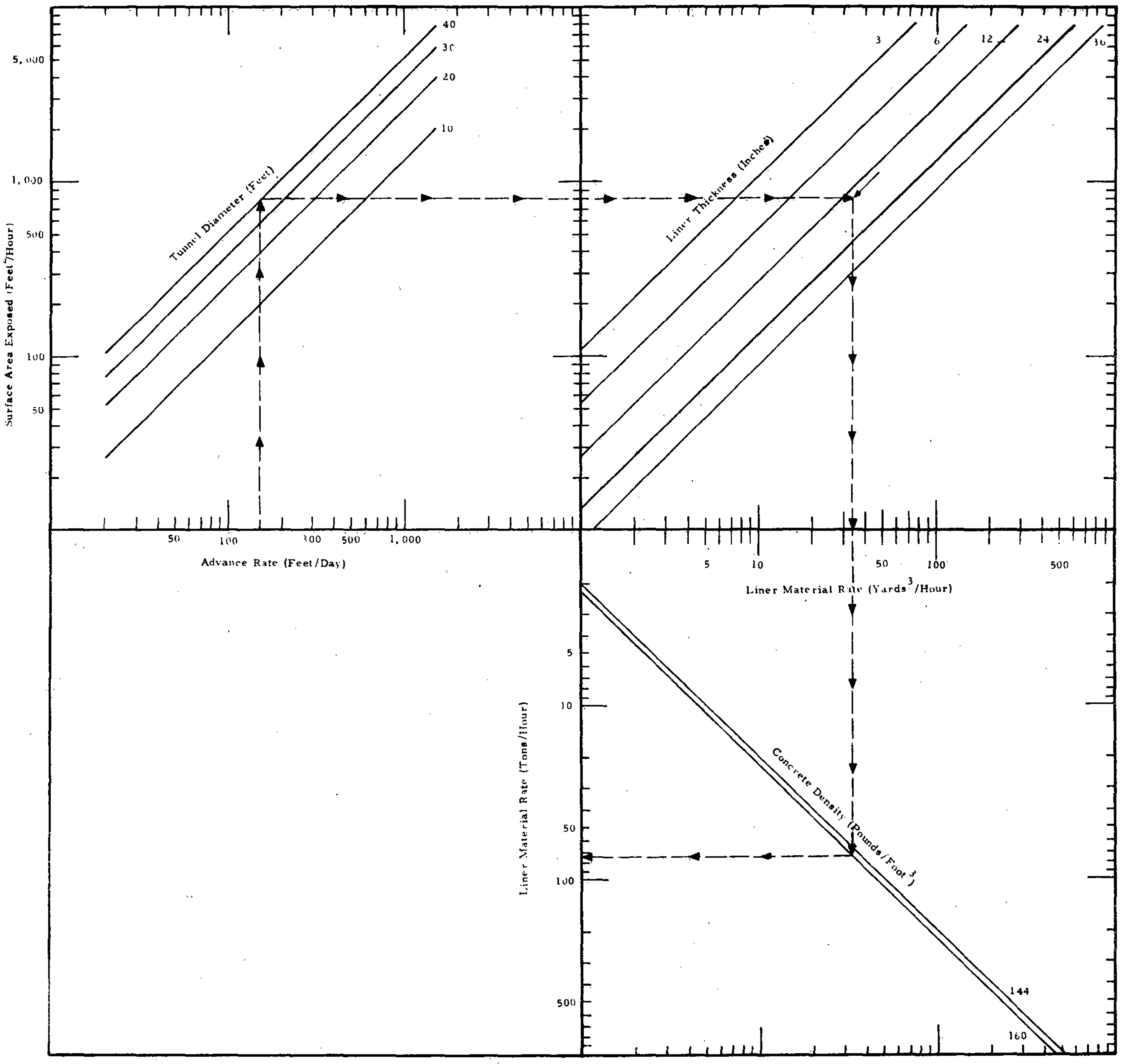


FIGURE 6-5

SHOTCRETE AND PRECAST LINER QUANTITIES

TABLE 6-2

QUANTITIES OF SHOTCRETE

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)							
	10		20		30		40	
	Cubic Yards per Hour	Tons per Hour	Cubic Yards per Hour	Tons per Hour	Cubic Yards per Hour	Tons per Hour	Cubic Yards per Hour	Tons per Hour
300	7	16	17	36	36	78	68	147
500	12	27	28	60	60	130	113	245
750	18	40	43	90	90	195	170	367
1,500	35	80	85	180	180	390	340	735

NOTES

1. Shotcrete density is assumed = 160 pounds per cubic foot.
2. Shotcrete thicknesses for the tunnel diameters are:
   - 10-foot diameter = 6 inches thick
   - 20-foot diameter = 7 inches thick
   - 30-foot diameter = 10 inches thick
   - 40-foot diameter = 14 inches thick
3. Shotcrete is assumed to be 100 percent effective; that is, the material does not bounce off during application.

Precast Concrete Liners - The number of units and tons per hour of precast concrete liners, obtained from Figure 6-5, to support the various combinations of advance rate and tunnel diameter are shown in Table 6-3. The liners consist of varying thicknesses of concrete poured about "H" or wide flange steel beams. The dimensions of the structural steel are scaled up as the tunnel diameter is increased. All liner segments are assumed to be 4 feet wide and are placed continuously; that is, each emplaced liner butts up against the previously emplaced liner. Each set of liners consists of 3, 4, 8, or 10 units, depending on the tunnel diameter. The liner ton-per-hour requirements are larger than for the shotcrete technique, and the ratio of muck tonnage to liner tonnage is about 7.6:1 except for the 10-foot tunnel where it falls to about 6:1. The number of units that must be emplaced per hour go from a low of 9.4 units weighing about 1.6 tons each to a maximum of 156 units per hour weighing about 6.6 tons each.

The massiveness, size, and peculiar shape of precast concrete liners pose some difficult material handling problems. Each unit is shaped like a portion of an annulus with an arc length of 10.5 to 12.5 feet. To package a typical liner unit, the general dimensions of the package would be 4 feet wide by 2 feet high by 12 feet long. The transport and transfer of these units, therefore, require rather large capacity equipment that can accommodate unwieldy, curve-shaped units. For transferring these units, that is, loading and unloading the transport system and emplacing the liners, it is apparent that specially designed equipment is required.

Ribs and Lagging - The tons per hour of ribs and lagging to support the various combinations of advance rate and tunnel diameter are shown in Table 6-4. Lagging quantity rates may be obtained from Figure 6-6 for various advance rates, tunnel diameters, wall coverage, lagging thickness and density. Rib sets are comprised of 3, 4, 6, or 10 ribs of varying thicknesses, depending on the tunnel diameter. Each rib set is assumed to be spaced 4 feet from the previous set, thus providing only intermittent support. In addition to the rib sets, lagging is assumed to be placed covering 90 degrees of the crown. Blocking is assumed to be necessary in aligning and setting the rib sets and is estimated to be 10 percent of the lagging requirements. No auxiliary construction materials such as nuts, bolts, purlins, and bracing are included in the figures. The steel rib ton-per-hour requirements are considerably less than for shotcrete and precast concrete liners. The ratio of muck tons per hour to ribs and lagging tons per hour is approximately 100:1, except for the 10-foot tunnel where it drops to about 50:1. The same number of steel rib units are required as for the precast concrete liners, that is, from 9.4 to 156 units per hour. Timber is required for lagging and blocking and accounts for a significant portion of the total ribs and lagging tonnage requirements. For the assumed conditions, the lagging and blocking

TABLE 6-3

QUANTITIES OF PRECAST CONCRETE LINERS

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)							
	10		20		30		40	
	Units per Hour	Tons per Hour	Units per Hour	Tons per Hour	Units per Hour	Tons per Hour	Units per Hour	Tons per Hour
300	9.4	16	15.6	50	25.0	115	31.2	207
500	15.6	27	26.0	83	41.7	192	52.0	345
750	23.4	40	39.0	125	62.5	287	78.0	518
1,500	46.8	80	78.0	250	125.0	575	156.0	1,035

NOTES

1. The liner dimensions and general design are:

   Unit weight = 1.6 tons for 10 ft - (2) 4 in. by 4 in. H 13 embedded in 6 in. thick by 4 ft wide by 10-1/2 ft arc length units (3 units/set);
   = 3.2 tons for 20 ft - (2) 6 in. by 6 in. H 20 embedded in 10 in. thick by 4 ft wide by 12-1/2 ft arc length units (5 units/set);
   = 4.6 tons for 30 ft - (2) 8 in. by 8 in. H 34.3 embedded in 15 in. thick by 4 ft wide by 11-2/3 ft arc length units (8 units/set);
   = 6.6 tons for 40 ft - (2) 10 in. by 10 in. WF 49 embedded in 20 in. thick by 4 ft wide by 12-1/2 ft arc length units (10 units/set).
2. Concrete density assumed = 144 pounds per cubic foot.
3. Excluded are any auxiliary nuts, bolts, connectors or other materials.

TABLE 6-4

QUANTITIES OF RIBS AND LAGGING

Advance Rate (ft/day)	Item	Tunnel Diameter (Feet)							
		10		20		30		40	
		UPH	TPH	UPH	TPH	UPH	TPH	UPH	TPH
300	Ribs	9.4	0.99	15.6	3.10	25.0	7.10	31.2	12.60
	Lagging		0.50		1.00		1.50		2.00
	Blocking		0.05		0.10		0.13		0.20
	Total		1.54		4.20		8.75		14.80
500	Ribs	15.6	1.60	26.0	5.10	41.7	11.80	52.0	21.00
	Lagging		0.80		1.67		2.50		3.30
	Blocking		0.08		0.17		0.25		0.33
	Total		2.48		6.94		14.55		24.63
750	Ribs	23.4	2.50	38.9	7.70	62.5	16.20	78.0	31.40
	Lagging		1.25		2.50		3.70		5.00
	Blocking		0.13		0.25		0.37		0.50
	Total		3.88		10.45		20.27		36.90
1,500	Ribs	46.8	4.90	78.0	15.40	125.0	35.60	156.0	59.60
	Lagging		2.50		5.00		7.50		10.00
	Blocking		0.25		0.50		0.75		1.00
	Total		7.65		20.90		43.85		70.60

NOTES

1. UPH = Units per Hour, TPH = Tons per Hour.
2. Rib dimensions and general design for:
   10' tunnel 6"x 6" H 20.0x10.5 arc length @ 210 lb/rib (3 ribs/set)
   20' tunnel 8"x 8" H 34.3x15.5 arc length @ 532 lb/rib (4 ribs/set)
   30' tunnel 10"x10" WF 49.0x15.5 arc length @ 760 lb/rib (6 ribs/set)
   40' tunnel 12"x12" WF 65.0x12.5 arc length @ 812 lb/rib (10 ribs/set)
3. Bore configuration is circular. Lagging covers 90 degrees about crown centerline and consists of 4" thick timber weighing 30 lb/ft^3.
4. Blocking is assumed to be 10 percent of lagging tonnage requirements.
5. No auxiliary materials such as purlins, tie rods or traces are included.
6. Rib sets are spaced 4 feet apart.

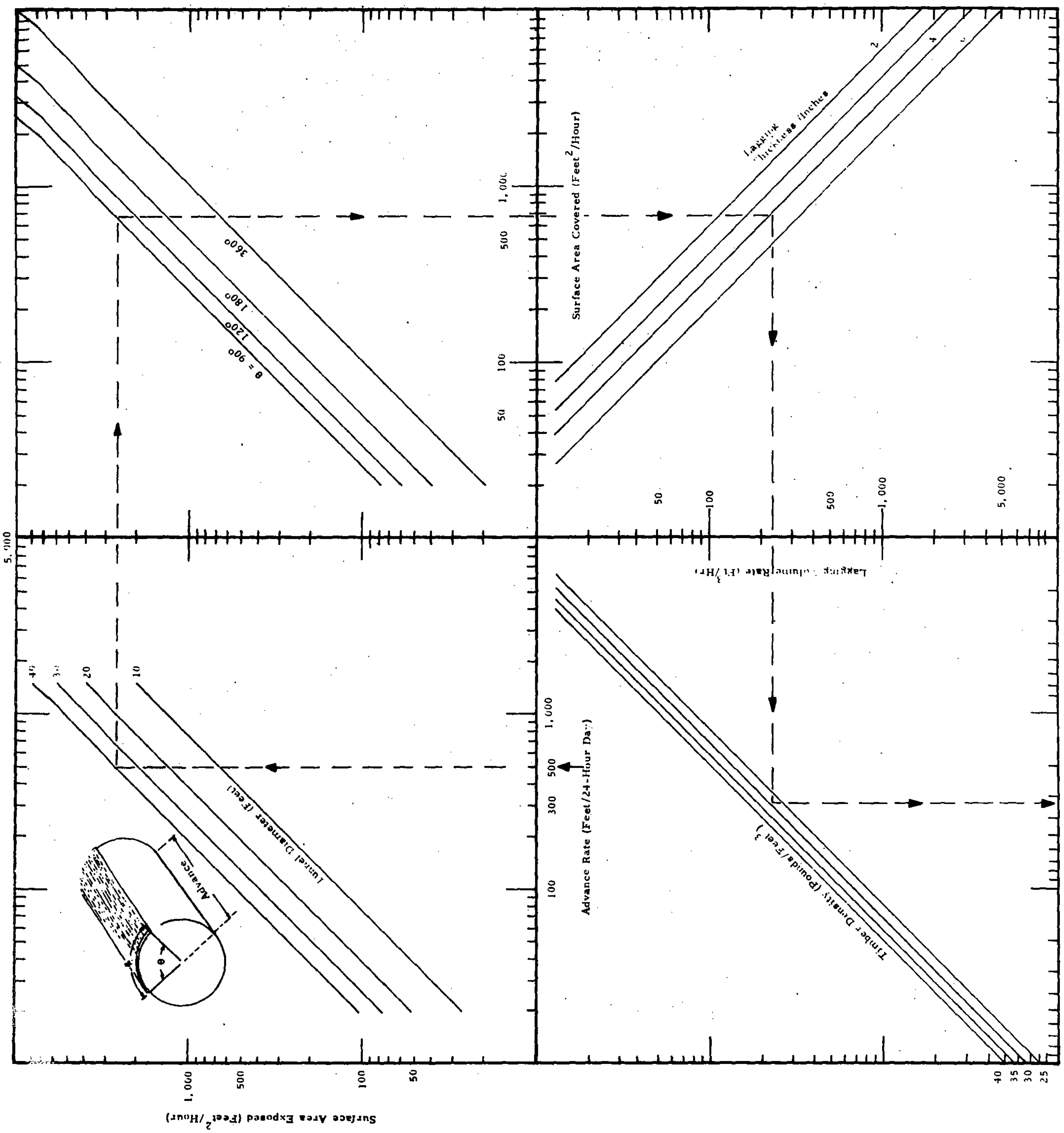


FIGURE 6-6

LAGGING QUANTITIES

portion of the total tons per hour is about 30 percent, 25 percent, 20 percent, and 15 percent for the 10-foot, 20-foot, 30-foot, and 40-foot diameter tunnels, respectively. The variation of the percentages with tunnel diameter is due to the use of more massive steel ribs with each increase in diameter. If full, continuous lagging (360-degree coverage) is used instead of the 90-degree coverage, the timber requirements approach that of the steel requirements; and in the case of the 10-foot tunnel, they actually exceed the tons per hour of steel required.

The shape of the ribs is an annulus segment as in the case of the precast concrete liners. The massiveness, however, is considerably less. The ribs are curved steel beams 10.5 to 15.5 feet long, weighing 0.1 to 0.4 tons each. The ribs can be easily transported by conventional rail or truck material handling systems. This unwieldiness, however, may preclude the use of other types of other types of transport.

Rock Bolts - The number of rock bolt tons-per-hour to support the various advance rates and tunnel diameters can be obtained from Figure 6-7 and are summarized in Table 6-5. The bolt sizes, weights, and spacing are estimated requirements and are not based on specific designs. A comparison of the tons per hour of muck with the rock bolt tons-per-hour shows a ratio of about 1500:1 except for the 10-foot tunnel where it drops to 1000:1. If wire mesh were included with the rock bolts, or if the tunnel crowns were completely covered (180-degree coverage) with rock bolts only, the bolt tons-per-hour would approximately double. Of all the types of ground support discussed, rock bolts present the least tons per hour transport requirements.

Rock bolts are usually received and transported to the near-face zone in bundles. Each bundle may have 10 or more rock bolts which are strapped together to form a shipping package. The impact of rock bolts on material handling requirements is therefore a function of the number, size, and weight of the shipping packages. These packages can be fairly heavy. In the 40-foot tunnel, for example, the rock bolts weigh 70 pounds each and a package of 10 bolts would weigh 700 pounds. Transfer equipment must be capable of on-loading these packages at the collar or portal and off-loading the packages in the near face zone. The accessories (nuts and plates) are usually packaged in barrels.

The quantities of shotcrete, precast concrete liners, ribs, and rock bolts presented in the previous tables are summarized in graphical form in Figure 6-8. The muck-removal requirements for the same conditions are shown also as a reference. The tonnage requirements for precast liners and for shotcrete are both large and of roughly the same magnitude. The use of different sizes or design of precast liners could easily cause their requirements to converge with the shotcrete requirements.

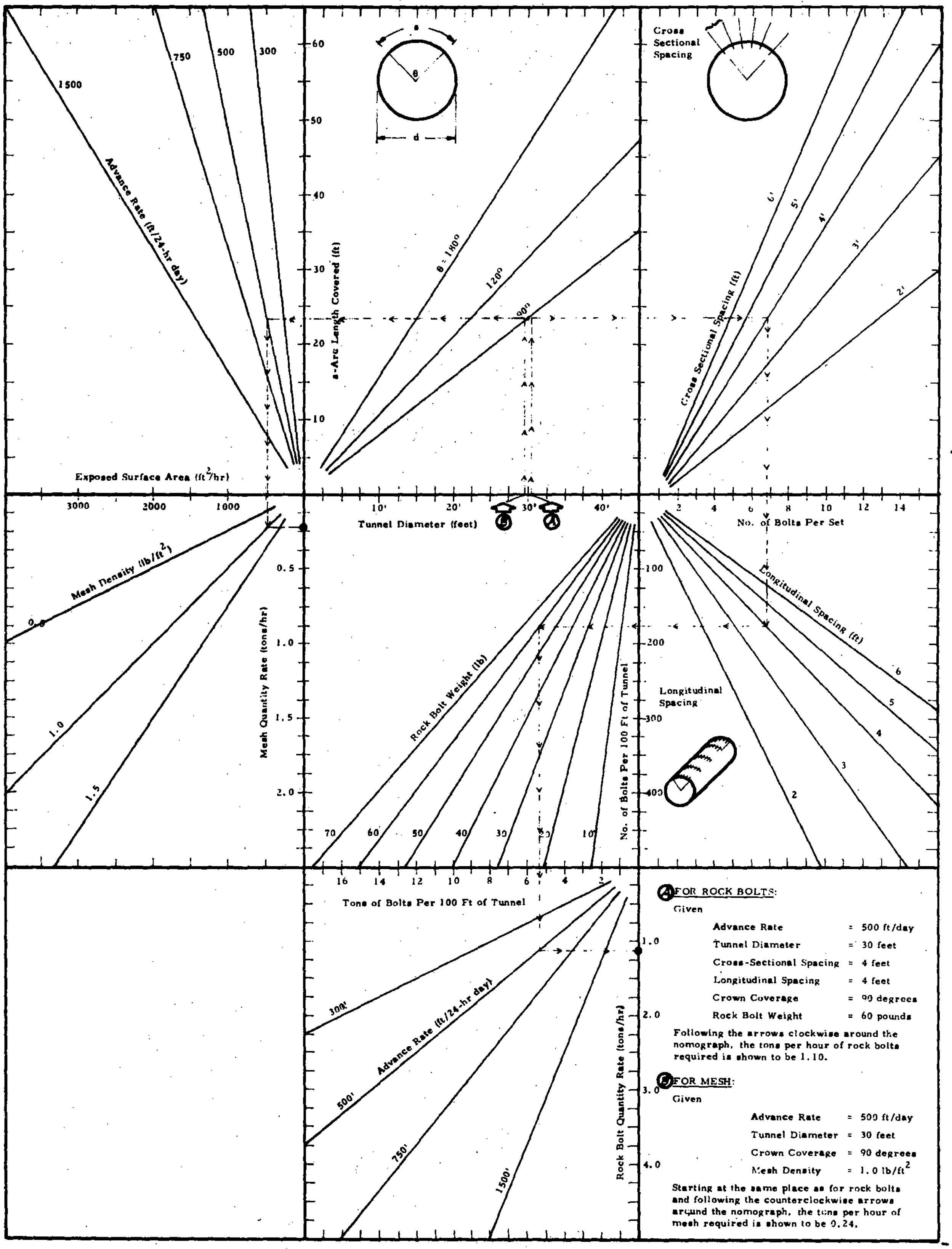


FIGURE 6-7

ROCK BOLT AND MESH QUANTITIES

TABLE 6-5

QUANTITIES OF ROCK BOLTS

Advance Rate (ft/day)	Item	Tunnel Diameter (Feet)							
		10		20		30		40	
		UPH	TPH	UPH	TPH	UPH	TPH	UPH	TPH
300	Rock Bolts	14	0.07	18	0.20	22	0.67	29	1.00
	Accessories		0.01		0.02		0.07		0.10
	Total		0.08		0.22		0.74		1.10
500	Rock Bolts	23	0.12	30	0.33	37	1.10	48	1.67
	Accessories		0.01		0.03		0.11		0.17
	Total		0.13		0.36		1.21		1.84
750	Rock Bolts	35	0.17	45	0.50	55	1.67	73	2.50
	Accessories		0.02		0.05		0.17		0.25
	Total		0.19		0.55		1.84		2.75
1,500	Rock Bolts	70	0.35	90	1.00	110	3.35	145	5.00
	Accessories		0.04		0.10		0.34		0.50
	Total		0.39		1.10		3.69		5.50

NOTES

1. UPH = Units per Hour, TPH = Tons per Hour.
2. Accessories, nuts and plates, are estimated at 10 percent of the rock bolt unit weight.
3. The estimated rock bolt sizes and weights are:

Tunnel Diameter (feet)	Bolt Diameter (inches)	Length (feet)	Approximate Weight (pounds)
10	3/4	6	10
20	1	8	22
30	1-1/2	10	60
40	1-5/8	10	70

4. These are assumed to be expanding bolts requiring no wedges or grout.
5. A 90-degree section of the circular tunnel is assumed to be covered with a 4-foot by 4-foot spacing pattern.

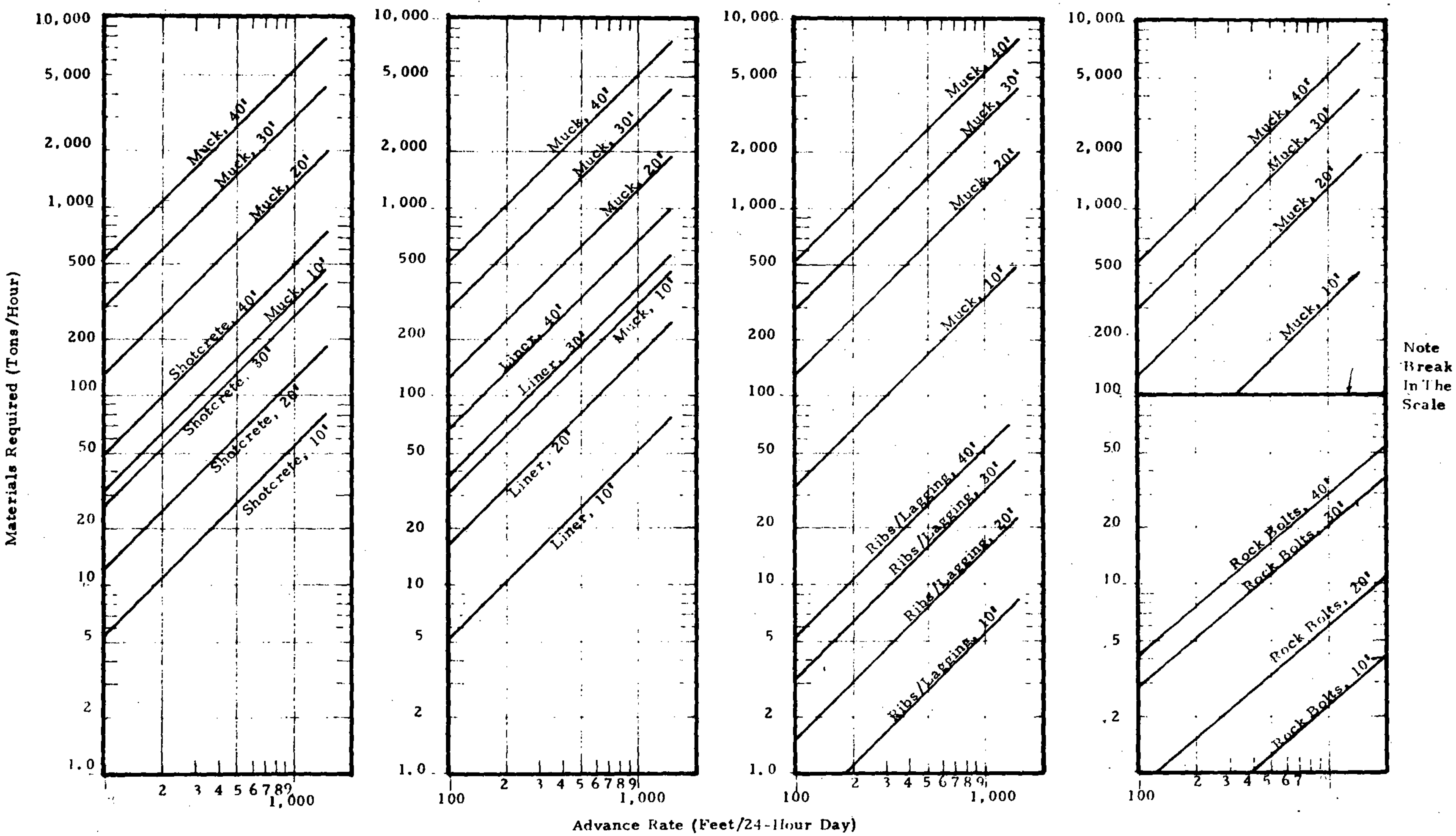


FIGURE 6-8

COMPARISON OF GROUND SUPPORT MATERIAL QUANTITIES

Conversely, in the application of shotcrete all of the material applied was assumed to remain in place. In actual practice, as much as 45 percent may rebound and thus more material is required than that called for by the design thickness. Incorporation of this factor could increase the shotcrete requirements significantly. There is considerable optimism for the future use of the shotcrete techniques. This expectation could result in comparatively large tonnage requirements for the future material handling system.

The rib-and-lagging ground support technique tonnage requirements are approximately an order of magnitude less than the shotcrete or liner techniques. The reason for this is that the use of liners or shotcrete provides continuous ground support while rib and lagging is an intermittent type of ground support. However, the number of ribs requiring transport to the near-face zone is the same as for the precast concrete liners. Since these ribs are curved steel segments 10.5 to 15.5 feet long, they are unwieldy and with the added requirements of timber, presumably in packages, the total overall material handling system requirements may approach those for the precast concrete liners.

Materials for Systems Extension

The quantity rate of extension materials is dependent on the advance rate, bore configuration, and design of the extension technique. The advance rate establishes the length that material handling systems must be extended per time unit. This extension usually consists of laying a road or track bed on the tunnel floor and then emplacing the additional material handling system segments upon the bed.

The quantity rate requirements for extension materials for road and rail bed systems are presented in Tables 6-6 and 6-7. These types of material transport systems require a greater flow rate of material for system extension than any of the other systems considered. Quantity requirements for other systems are given in Chapter 9. Table 6-6 is for the construction method of laying ballast and emplacing ties, rails, and accessories and Table 6-7 is for emplacing prefabricated platforms with rails attached to the platforms. If roadbeds only are required, the ties, rails, and accessory tonnage requirements can be deleted to yield the roadbed tonnage requirements. These requirements were generated for two-way transport systems, that is, double-lane or double-track systems with a given span.

Ballast, Ties, Rails, and Accessories - The ton-per-hour requirements of laying beds with ballast, ties, rails, and accessories are shown in Table 6-6 for various advance rates, bore configurations, and tunnel diameters. The amount of ballast required depends on whether the bore

TABLE 6-6

QUANTITIES OF BALLAST, RAILS, TIES, AND ACCESSORIES

Advance Rate (ft/day)	Item	Tunnel Diameter (Feet) 10 Circular (T/hr)	10 Sidewall (T/hr)	20 Circular (T/hr)	20 Sidewall (T/hr)	30 Circular (T/hr)	30 Sidewall (T/hr)	40 Circular (T/hr)	40 Sidewall (T/hr)
300	Ballast	4.10	4.20	9.30	6.90	43.70	13.70	28.00	13.70
	Rails & Acc	0.54	0.54	0.54	0.54	0.84	0.84	0.84	0.84
	Ties	0.33	0.33	0.33	0.33	0.66	0.66	0.66	0.66
	Total	4.97	5.07	10.17	7.77	45.20	15.20	29.50	15.20
500	Ballast	6.83	6.90	15.50	11.40	72.83	22.80	46.67	22.80
	Rails & Acc	0.87	0.87	0.87	0.87	1.40	1.40	1.40	1.40
	Ties	0.55	0.55	0.55	0.55	1.10	1.10	1.10	1.10
	Total	8.25	8.32	16.92	12.82	75.33	25.30	49.17	25.30
750	Ballast	10.25	10.40	23.25	17.10	109.25	34.20	70.00	34.20
	Rails & Acc	1.30	1.30	1.30	1.30	2.10	2.10	2.10	2.10
	Ties	0.83	0.83	0.83	0.83	1.66	1.66	1.66	1.66
	Total	12.38	12.53	25.38	19.23	113.01	37.96	73.76	37.96
1,500	Ballast	20.50	20.80	46.50	34.10	218.50	68.20	140.00	68.20
	Rails & Acc	2.60	2.60	2.60	2.60	4.20	4.20	4.20	4.20
	Ties	1.65	1.65	1.65	1.65	3.30	3.30	3.30	3.30
	Total	24.75	25.05	50.75	38.35	226.00	75.70	147.50	75.70

NOTES

1. Ballast material is loose, dry gravel at 95 lb/ft^3.
2. Ballast requirements are for double lane road or double track rail beds.
3. For circular tunnels, the height above the tunnel floor required to fit in the spans are: 1-1/2 feet for the 10-foot, 2 feet for the 20-foot, 5 feet for the 30-foot, and 3 feet for the 40-foot.

TABLE 6-7

QUANTITIES OF PLATFORMS

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)							
	10		20		30		40	
	Units per Hour	Tons per Hour	Units per Hour	Tons per Hour	Units per Hour	Tons per Hour	Units per Hour	Tons per Hour
300	3.2	1.7	3.2	3.0	3.2	7.2	3.2	7.2
500	5.2	2.9	5.2	4.9	5.2	11.6	5.2	11.6
750	7.8	4.3	7.8	7.4	7.8	17.2	7.8	17.2
1,500	15.7	8.7	15.7	14.9	15.7	35.2	15.7	35.2

configuration is circular or vertical sidewall. For circular tunnels, sufficient ballast must be laid to provide a bed of sufficient cross-sectional span to accommodate the material handling system. Typical spans were estimated to be 6-1/2 feet for the 10-foot tunnel, 11 feet for the 20-foot tunnel, and 22 feet for the 30-foot and 40-foot tunnels. The 22-foot span was based on a standard-sized, double-track rail system. The 6-1/2-foot and 11-foot spans were the estimated spans required for specialized rail or truck systems. In order to achieve these spans, the bed must be raised from the tunnel floor some distance. To achieve the same span in a 30-foot tunnel as in a 40-foot tunnel, the bed must be higher from the invert. This results in more ballast and explains why the 30-foot tunnel requirements in Figure 6-6 are greater than for the 40-foot tunnel.

For vertical sidewall tunnels, the beds are constructed on a reasonably flat, wide surface and therefore do not require raising up to achieve the required span. The tonnage requirements for the 10-foot vertical side-wall tunnel are about the same as for the 10-foot circular tunnel. For the 20-foot tunnel the vertical sidewall requirements are roughly 80 percent of the circular tunnel. For the 30-foot and 40-foot tunnels the vertical sidewall requirements are roughly one-third and one-half, respectively, of the circular tunnel requirements. The bore configuration can thus strongly influence these requirements. The ties, rails, and accessories tonnages are relatively small compared to the ballast tonnages.

Platforms - The quantity rates of platforms are shown in Table 6-7. These rates are based on the platform design discussed in Chapter 9 and include the weight of attached double track for rail systems. For road-beds, the rail would not be required. The tons per hour of platforms required are much less than for the ballast method. This is due to the fact that platforms span a segment of the tunnel and do not require, as in the case of ballast, the spanned area to be filled in with material. For circular tunnels, the platform quantity rates are about 50 percent of the ballast rates for the 10- and 20-foot diameters. For the 30-foot and 40-foot tunnels, these rates drop to approximately 19 and 29 percent, respectively, of the ballast rates.

QUANTITY RANGES OF MATERIALS

The quantity ranges of materials requiring transport within the tunnel complex are shown in Figure 6-9 as a function of advance rate and tunnel diameter. The materials have been grouped by operation and reflect the maximum and minimum values of each group independently of the other groups and without regard to a specific tunnel system design. For example, the upper bound for ground support materials represents precast liners and the lower bound is for rock bolts. The other material ranges superimposed on the ground support material field show the quantity ranges of these materials relative to the range of ground support materials. For comparison, the quantity range of muck also is shown. These quantity ranges reflect the tonnage requirements that material handling systems must meet for the tunneling process and are based on the conditions assumed in this study.

The quantity rate of muck is based on an in-situ rock specific gravity of 2.6. The total range of muck quantities is from 95 tons per hour to 7,645 tons per hour for the 10-foot tunnel driven at 300 feet per day and the 40-foot tunnel driven at 1,500 feet per day, respectively. These numbers convert to 44 cubic yards per hour and 3,490 cubic yards per hour for an assumed swell factor of 20 percent. For purposes of muck-material comparisons, a single line is shown for the quantities of muck involved. However, there is a range of muck quantities depending on the rock conditions encountered and the tunnel bore configuration. The specific gravity of rock normally encountered will vary between 2.5 and 3.

The quantity rates of ground support materials cover the widest range. This range is based on four basic methods of ground support: precast concrete liners, shotcrete, ribs and lagging, and rock bolts. Of these, the precast concrete liners are the heaviest while the rock bolts are the lightest. The overall range for all tunnel diameter and advance rate conditions is from 0.1 tons per hour to 1,000 tons per hour. Actually, the range could begin from 0 since, for the most competent rock conditions, no primary ground support may be required. The ranges shown are for primary support only. If secondary support were assumed to be installed concurrently with the primary support, the maximum total ground support quantities would approximately double.

The range of material handling system extension materials is based on the use of ballast and the use of platforms. The total range of quantity rates is from about 2 tons per hour on the 10-foot tunnel advanced at 300 feet per day to 230 tons per hour on the 30-foot tunnel advanced at 1,500 feet per day. The extension material quantities do not increase linearly with tunnel diameter due to the interplay between the cross-sectional geometry of circular tunnels and the requirement for fitting in

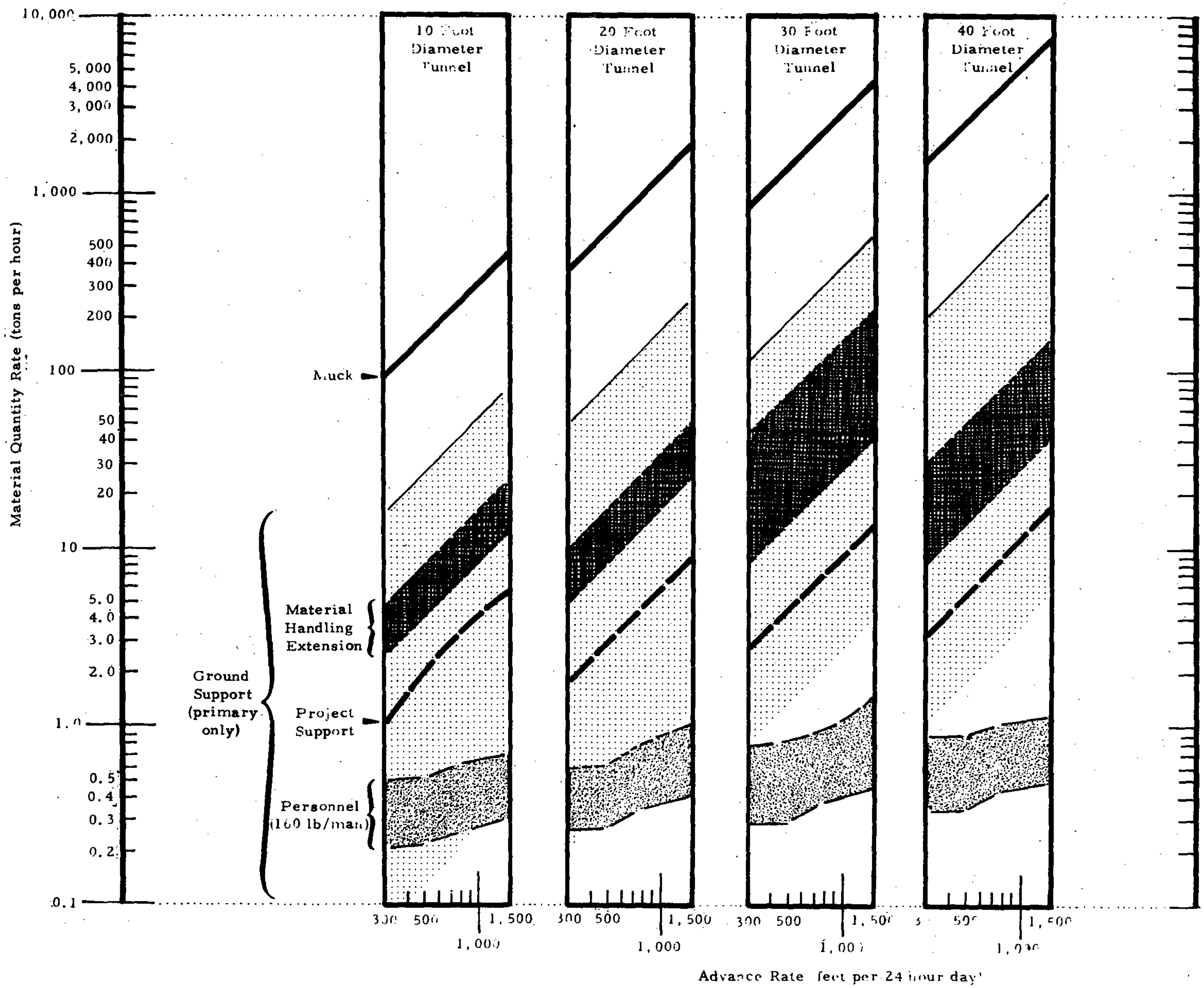


FIGURE 6-9

QUANTITY RANGES OF MATERIALS

a rail or roadbed with a given cross-sectional span. For the 30-foot tunnel, the bed must be raised from the tunnel floor 5 feet in order to achieve the span required for a standard-sized, double-track rail system. For the 40-foot tunnel, the bed must be raised only 3 feet. More materials are required to raise the bed 5 feet in the 30-foot tunnel than to raise it 3 feet in the 40-foot tunnel.

For project support, the quantity rates are shown as a line instead of a range. This is because the material quantities involved in the provision of project support tend to be functions of only the advance rate and tunnel diameter. The total range of material quantities varies from 1.2 tons per hour for the 10-foot tunnel driven at 300 feet per day to 16.9 tons per hour for the 40-foot tunnel at 1,500 feet per day.

Some interpretation is required in evaluating the personnel quantities expressed in tons per hour. These numbers were generated by taking the minimum and maximum crew sizes per shift developed in Chapter 10 for each of the operations. These were summed to represent the total tunnel crew size, that is, only those men who work within the tunnel complex. This crew size was then converted into tons by assuming an average weight per man of 160 pounds. The ton-per-hour requirements were then determined by dividing the total tons per shift by 8 hours. The resulting figures should be considered artificial since, in general, personnel are transported more on an intermittent basis than continuously. A surge in the personnel transport requirements occurs at the beginning and end of each shift. Nevertheless, the numbers were converted to a ton-per-hour basis to provide some means of direct comparison with the other numbers.

The personnel requirements do not change appreciably with the advance rate or tunnel size. This results from the assumptions used in generating the crew sizes. As the advance rates and tunnel diameters were increased, the degree of automation involved was assumed to increase as well. This assumption was deemed necessary to preclude impossible numbers of men working in the same areas. Another interesting point involves the larger crew sizes needed in the 30-foot tunnel at the higher advance rates than for the 40-foot tunnel. This is due primarily to the increased number of truck drivers operating the 20-ton trucks needed in the 30-foot tunnel rather than the number of drivers operating the 50-ton trucks in the 40-foot tunnel.

A comparison of the muck quantities with the maximum and minimum combined ground support, material handling system extension, project support, and personnel quantity rate requirements is shown in Table 6-8.

TABLE 6-8

RATIO OF OTHER SUBSTANCES TO MUCK
(Percent of Muck Quantity)

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300 Minimum	3.0	1.5	1.1	0.7
1,500 Maximum	24.0	16.3	19.0	17.1

The above figures do not include the impact of concurrent emplacement of secondary lining. If the requirements for secondary lining are included, the maximum values for the 10-foot, 20-foot, 30-foot, and 40-foot tunnels would change to roughly 40, 29, 32, and 30 percent, respectively.

The overall flow of substances within the tunnel complex is dominated by the outbound flow of muck. The inbound flow of substances is dominated by ground support materials. Next, in terms of inbound tons-per-hour, are the materials required for material handling system extension followed by the project support material requirements.

CHAPTER 7

MUCK CHARACTERISTICS

SUMMARY

The determination of muck characteristics related to lithology, rock engineering properties, and method of excavation of in-situ rock is an area in which very little research or investigative effort has been expended. There has been, however, considerable research and development directed toward the relationship of the engineering properties to drillability, excavation, and underground support. Recent publications[1] correlate the extensive research and testing in this field as related to underground support.

Many other investigators have shown correlation between the physical engineering properties of the in-situ rock and the relative drillability, the hardness, and the abrasiveness; further, they have shown the effect of fractures, faults, and shear zones. In addition, there is an indication that a correlation exists between the physical properties of the rock and the characteristics of the resultant muck produced by various excavation systems. This will be explained in more detail later in this chapter; but, briefly, an attempt has been made to arrive at a means of identification of the various types of muck as related to the excavation process and engineering properties. This relationship has been identified as the Muckability Designation Number (MDN).

MUCK AS RELATED TO ENGINEERING PROPERTIES

The rock structure of the proposed tunnel line between Boston, Massachusetts, and Washington, D. C., known as the Northeast Corridor, has been chosen to illustrate the method of identification. Sufficient information in this area is not available, but it will serve to illustrate the process.

Relationship of Engineering Properties, Muck, and RQD

U. S. Geological Survey (USGS) maps and geological information of the Northeast Corridor (Reference 2, Map A) are the primary sources of data. The Map Unit numbers (Figures 7-1 and 7-2), of which there are 24, are identified by a very detailed lithological description. The dry unit weight, compressive strength, Young's modulus of elasticity, and relative drillability are also given. Using this information, the Rock Quality Designation (RQD) has been extrapolated in accordance with correlations as established by Stagg and Zienkiewicz[3] and Deere, et al.[4]

MAP UNIT	LITHOLOGY	PHYSICAL PROPERTIES			ESTIMATED ROCK QUALITY DESIGNATION (RQD) (%)	RELATIVE DRILLABILITY (RD)	MUCKABILITY DESIGNATION NUMBER (MDN)
		DRY UNIT WEIGHT (LBS/CU FT)	COMPRESSIVE STRENGTH	YOUNG'S MODULUS OF ELASTICITY			
1. Biotite-quartz-feldspar gneiss.	Medium-grained biotite-quartz-feldspar gneiss, with some hornblende locally. Commonly interlayered with epidote-bearing gneiss, amphibolite, and numberous intricately injected, pinching and swelling sheets of granite, aplite, and pegmatite.	163 - 173	Low to high.	Medium to high.	25-90	3	1-3
2. Amphibolite, epidote amphibolite, and metamorphosed gabbro.	Massive to banded, tough, strong amphibolite, amphibolite schist, amphibolite gneiss, hornblende gneiss; in part metagabbroic. Forms extensive thick layers, lenses, and pods. Commonly epidote-bearing, much epidote-rich amphibolite gneiss, and pods of epidote. Includes extensive thick light-red to pink garnet-rich layers. In places schistose toward margins; locally intruded by quartz diorite dikes.	187-200	High to very high.	High to very high.	90-100	2	1-2
3. Layered gneiss.	Strongly banded gneiss; layers differ sharply in composition. In Pennsylvania and Maryland consists of either interlayered quartz amphibolite, granulite, and light-colored biotite-quartz-plagioclase gneiss where grade of metamorphis high, or greenstone and schistose consist of biotite-quartz-feldspar gneiss, mica schist, granulite, amphibolite, and hornblende gneiss. Layers 1/2 inch to at least 100 feet thick. Cut by quartz veins, pegmatite, and granitic dikes and sills.	170-187	Medium to high.	Medium to high.	75-90	3	1-4
4. Gabbro.	Generally massive, dense, tough, medium-to-coarse-grained, dark green to purple or black gabbro; composition varies internally, commonly by layers. In part biotite rich, in part quartz bearing. Locally includes other rock types: norite, diorite pyroxenite, peridotite, and amphibolite.	184-193	High to very high.	High to very high.	90-100	2	1-2
5. Diorite and quartz gabbro.	Mixed zone of quartz-bearing gabbroic rocks, hornblende rich quartz diorite and hornblende diorite. Mostly fine to medium grained, strongly foliated in places. Includes many dikes and sills of granite and aplite, and contains many xenoliths..	181-193	High to very high.	Low to high.	25-90	2	1-4
6. Granitic rocks.	In general, individual bodies markedly homogeneous in composition and texture. Local variations. Aplites, pegmatites, mafic dikes, segregations, locally, in great abundance in some places.	170-185	Medium to high.	Low to medium.	75-100	2	1-2
7. Serpentinite, steatite, and related ultramafic rocks.	Serpentinite, massive or schistose; steatite, schistose or massive talc, talc actinolites, and chlorite -- containing schists and talc-carbonate-quarts rock. Massive serpentinite generally occurs in thick lenticular bodies; steatite and associated schists occur in thin sheets and lenses, and as rims around and along shear zones within massive serpentinite bodies. Unaltered dunite, peridotite, and pyroxenite occur locally. Rock is generally a mixture of tough hard fragments as much as 5 feet in diameter embedded in a very soft, weak, and highly sheared matrix. Color light green, greenish gray, to greenish brown.	161-178	Very low (sheared serpentinite and talc) to very high (unsheared serpentinite).	Very low to high.	0-100	2-5	1-7
8. Anorthosite.	Medium-to-coarse-grained, massive, exceedingly tough andesine anorthosite; blue-gray color very characteristic. Cut by a few basic dikes and pegmatites, otherwise markedly homogeneous.	164-170	Medium to high.	Medium to high.	50-90	4	1-3
9. Quartzite with interbedded conglomerate, schist, and gneiss.	Fine-to-medium-grained, vitreous to granular, generally pure but locally micaceous or feldspathic quartzite, interbedded with quartz schist, quartz-pebble conglomerate (occurs especially at base of unit), mica schist, conglomerate, and feldspar-quartz-biotite gneiss. Thin bedded or flaggy to thick bedded; bedding distinct to lacking. In many areas, quartz grains in the rock scarcely recrystallized; elsewhere the quartzite is wholly crystalline. Where crystalline, rock is very tough and hard; where scarcely recrystallized, similar to sandstone. Pegmatites and quartz veins irregularly spaced through the rock.	165-172	Medium to high.	Mostly high; schist low.	25-90	3	1-5
10. Marble, crystalline limestone, and dolomite.	In areas of medium to high metamorphic grade, generally associated with map unit 11: calcite marble, dolomite marble, and calc-silicate schist and gneiss; some interbedded thin layers of mica schist and graphite schist. Other areas, generally along northwest border of map area; limestone and dolomite, commonly recrystallized, in places interbedded; thin-to-thick bedded, locally finely laminated or massive; in places interbedded with phyllite, shale, and thin argillaceous partings; locally sandy. Generally fine-to-medium-grained, light to dark gray; locally white, bluish, or blue-black.	164-178	Medium (calcite) high (dolomitic marble).	Medium to high.	50-90	5	2-4
11. Coarse mica schist and mica gneiss.	Medium to coarsely crystalline, well-foliated schist and gneiss; biotite schist predominant; biotite gneiss, muscovite-biotite-schist, hornblende gneiss, muscovite schist, amphibolite schist, and granitized gneiss important; quartzite, amphibolite, and granulite common. Medium to high grade of metamorphism. Rock generally tough and strong. South of New England unit consists mostly of muscovite-biotite-quartz-plagioclase schist and minor mica gneiss, with some amphibolite; in New England, assemblage more varied. Large and small pegmatites and quartz veins, crosscutting and concordant, pervade the rock in New England; important but less abundant to the south.	165-176	Low to medium.	Low (schist) to high (gneiss).	25-90	5-6	2-3
12. Fine-grained mica schist, chlorite schist, and phyllite with interbedded quartzose rocks.	Fine-grained schist and phyllite composed chiefly of muscovite, chlorite, quartz, and sodic plagioclase; micaceous quartzite and metagraywacke rhythmically interbedded. In places, beds of pure quartzite, greenstone, and tuffaceous schist common. Rock generally competent and coherent, though less resistant and softer than map unit 11.	165-181	Very low to medium.	Mostly low, quartzite high.	25-90	3-5	3-6
13. Gneiss and schist, typically massive and granitic in appearance.	Heterogeneous pebble - and boulder - bearing metamorphic rocks of diverse appearance. Typically resemble medium-grained, weakly foliated granitic gneiss, but more strongly foliated locally; elsewhere massive, fine-grained, quartzitic. Contains rounded quartz pebbles and boulders, chips and fragments of mica schist, and blocks and slabs of metamorphic rock. Rock mineralogically uniform; quartz, plagioclase, and muscovite, 85 to 90 percent; and accessory biotite, chlorite, epidote magnetite and garnet. Tough and hard. Interpreted to be enormous, metamorphosed, folded submarine landslide deposit.	153-182	Low to high.	Medium to high.	50-90	3	1-3
14. Argillite, siliceous shale, slaty shale, slate, phyllite, and fine-grained schist.	Argillaceous rocks, variously metamorphosed. Include dense, dark argillite, siliceous shale, thin-bedded, locally carbonaceous, slaty shale, dark slate, phyllite, fine-grained quartz-mica schist and medium-grained quartz-mica schist and medium-grained quartz-albite schist. Most sequences incorporate sandstone and graywacke; locally limestone, and, in Boston, volcanic tuff.	148-177	Very low (phyllite) to high (slate).	Low to high.	25-90	5	3-6
15. Greenstone and greenschist.	Greenstone and greenschist, in part containing pods of quartz and lenses or porphyroblasts of epidote. Greenschist locally includes as much as 25 percent muscovite and 20 percent chlorite. Gray green to dark green.	168-191	Medium to very high.	High.	75-90		1-3
16. Volcanic rocks commonly altered and slightly metamorphosed.	Lava flows, welded tuffs and pyroclastic deposits with some feeder dikes and sills; strongly altered and slightly metamorphosed in part. Includes felsite, rhyolite, andesite, and some basalt. Textures range from glassy or flinty to finely crystalline, commonly porphyritic. Amygdaloidal rocks abundant. Tough, hard, resistant; commonly fractured. Rock type highly variable within short distances. In Maryland, metamorphosed to schist.	164-172	High.	High.	75-90		1-3

FIGURE 7-1

SUMMARIZATION OF GEOLOGIC AND ENGINEERING CONDITIONS
With Estimated Rock Quality Designation and Proposed Muckability Designation Numbers
(Data from USGS Maps 1-514 for Northeast Corridor)[2]

MAP UNIT	LITHOLOGY	PHYSICAL PROPERTIES: DRY UNIT WEIGHT (LBS/CU FT)	PHYSICAL PROPERTIES: COMPRESSIVE STRENGTH	PHYSICAL PROPERTIES: YOUNG'S MODULUS OF ELASTICITY	ROCK QUALITY DESIGNATION (RQD) (%)	RELATIVE DRILLABILITY (RD)	MUCKABILITY DESIGNATION NUMBER (MDN)
17. Sandstone and shale.	Fine-to-coarse-grained sandstone, lithic graywacke, graywacke, arkose, siltstone, shale, and some conglomerate. In southeastern New England, a complex, highly irregular interbedding of all facies, locally including beds of rhyolite, basalt, and meta-anthracite; coarser grained rocks more prevalent to the northeast. Conglomerate contains boulders as much as 4 feet in diameter; stones dominantly quartz and quartzite, felsite common locally. Rocks generally well indurated and strong; color gray to black, locally greenish, chiefly red in northerm part of outcrop area. Degree of metamorphism increases southward; rocks essentially nonmetamorphosed in the north; minerals of higher metamorphic grade appear successively southward. In New York and New Jersey, a single sequence of rocks: fine-grained quartz-pebble conglomerate at base, overlain by thick-bedded, weakly cemented, friable, greenish to light-gray sandstone, in part calcareous; thick-bedded, slaty to fissile, dark-gray to black argillaceous and partly siliceous shale; and thin-bedded, strong dark-gray sandstone.	140-166	Medium to high (sandstone).	Medium.	50-75		2-4
18. Limestone and shale.	Chiefly soft, red shale, about 200 feet thick. Also includes dark-gray limestone, impure, siliceous, shaly; about 50 feet thick.	135-168	Very low to medium.	Very low to medium.	0-75	5-5	5-7
19. Conglomerate.	Hard, resistant, coarse to fine conglomerate, containing lenses and beds of sandstone. Stones mostly pebbles and cobbles, but range in size from granules to boulders. Most gragments and subrounded or rounded; mainly quartz and quartzite, but locally include a wide variety of plutonic, volcanic, and metamorphic rocks. Matrix is sandstone, graywacke, shaly sandstone, or shale; in many places schistose. Mostly massive layers; bedding indistinct except in sandstone. In parts of Rhode Island and Massachusetts, matrix metamorphosed and pebbles stretched; unit incorporates layers and small bodies of volcanic rocks (map unit 16).	165-168	Medium to high.	High (conglomerate) to low (sandstone).	25-90	3-4	5-7
20. Chiefly red shale.	Chiefly thin-to-medium-bedded shale, but includes interbedded mudstone, siltstone, and fine-grained sandstone; locally includes thin limestone and gypsum beds. In Pennsylvania and New Jersey, lower beds thicker, upper beds generally thin and wavy. In Pennsylvania and New Jersey, lower beds thicker, upper beds generally thin and wavy. In Connecticut, beds finely laminated and fissile (locally "paper shales") in lower part, thickening upward. Generally weak, soft, breaks with hackly fracture. Chiefly red to reddish brown, in part dark gray to black; in Connecticut locally varicolored. Dominantly argillaceous, in part micaceous; siltstones and some sandstones somewhat arkosic.	140-166	Very low to medium.	Very low.	0-25	7	6-7
21. Mudstone	Mostly tough, massive to thick-bedded, homogeneous argillaceous mudstone, locally cemented and well indurated; extremely fine grained; breaks conchoidally; mostly dark gray to black; locally red. Composition dominantly illite; chlorite, plagioclase feldspars, dolomite, calcite also common. In some areas includes extensive platy, finely laminated, calcareous mudstone and marlstone, commonly pyritic; medium to dark gray. In southwestern area includes tough, thin-bedded siltstone and fine-grained sandstone, calcareous and micaceous; red to greenish gray.	162-172	Very low to medium.	Low to very low.	0-25	7	6-7
22. Red sandstone, shale and conglomerate.	Mainly medium-to-fine-grained, well-sorted, muscovite-rich arkose, and interbedded feldspathic sandstone, siltstone, and mudstone, with some fine-to-coarse-grained conglomerate in lower parts, generally as channel fillings and large lenses. Along easternmost margin in Connecticut contains small fanglomerates similar to those of map unit 24. Locally includes thin limestone and gypsum beds. Arkose has interlocking grains, 50 to 70 percent quartz, 15 to 40 percent feldspar, cemented by silica and calcite. Conglomerate pebbles chiefly quartz and quartzite, some phyllite; average 1-inch diameter, maximum about 14 inches. Stones moderately rounded to subangular, in coarse-grained matrix, quartz and orthoclase grains rounded to angular. Rock yellowish gray to reddish brown. Maximum thickness about 5,000 feet.	156-165	Very low to high.	Mostly low, shales very low.	0-25	6	5-7
23. Basaltic rocks.	Mafic igneous rock; medium gray to black; tough, strong; fine-to-medium-grained. Includes lava flows, sills, and dikes. Basal part of some dikes and sills olivine rich. Some sheets contain as many as nine separate flows. Sills and dikes as much as 1,500 feet thick. Multiflow formations 30 to 80 feet thick.	175-189	Medium to very high.	High	75-90	1	1-2
24. Conglomerate	Two types of pebble to cobble conglomerate, both with matrix of red to brown coarse sandstone to siltstone. Stones in one type generally rounded, in part subangular; dominantly quartzitic, some conglomerate, a few limestone. Stones in other type angular and wholly of limestone. Both contain scattered beds of arkosic sandstone and siltstone.	165-168	Medium to high.	Low.	25-90	6	5-7

GENERAL NOTES

(1) The stratigraphic nomenclature used in this report is that of the authors of the various data sources and does not necessarily conform with usage of the U.S. Geological Survey.

(2) Physical data available only for some rock units; where data are lacking, the physical properties are inferred from comparisons with those of rock elsewhere that possesses similar composition, structure, and geologic histories.

(3) Reported construction characteristics are limited in number. Evaluations of rock units, for the most part, are inferred from generalized conditions of structure, alteration, hydrology, and state of stress. Specific conditions can change within short distance. More refined engineering evaluations must be based on more detailed knowledge of geologic conditions.

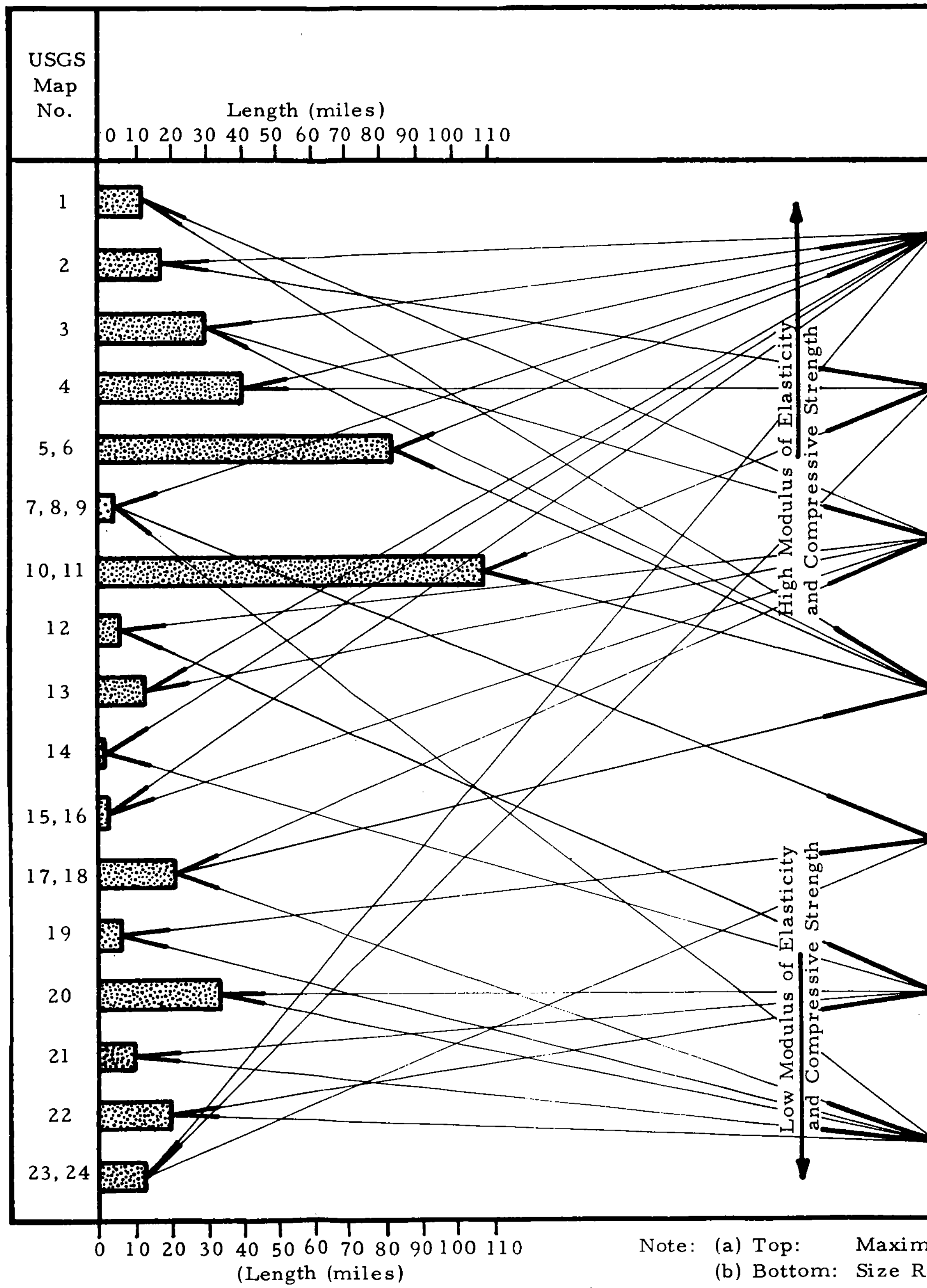
(4) The well-yield data used in the preparation of the Hydrologic Table (not shown here) are based on public-supply and industrial wells in which the maximum potential of the aquifer was being developed.

(5) Classification is for uniaxial compressive strength of intact rock. Strength is reduced by physical defects and chemical alteration in rock; it may differ with respect to bedding, foliation, or direction of principal residual stress. Strength Class -- Compressibility Strength relationships are as follows: Very high -- >32,000; High -- 16,000 - 32,000; Medium -- 8,000 - 16,000; Low -- 4,000 - 8,000; and Very Low -- <4,000.

(6) Inferred for intact rock. Modulus is reduced by physical defects and chemical alteration in rock; it differs with respect to bedding, foliation, or direction of principal residual stress. Modulus Class - Static Modulus of Elasticity relationships are as follows: Very high -- $>12 \times 10^6$; High -- 8×10^6 - 12×10^6; Medium -- 4×10^6 - 8×10^6; Low 1×10^6 - 4×10^6; and Very Low -- $< 10^6$.

(7) Number 1 (Relative Drillability) indicates rock most difficult to drill. Numbers increase with ease of drilling.

FIGURE 7-1 (continued)



Muckability Designation Number (MDN)	Blasted		Mechanically Excavated		Hydraulically Excavated	Thermal and Others
	Description	Size[(a)] Distribution	Description	Size Distribution	Size[(a)(b)] Distribution	Size[(a)(c)] Distribution
1	Blocky	18" x 24" 1"-100 mesh	Fines and Foliated	1"x1"mesh 1/2" - 200m	1" x 1" 1/2" - 200m	1/2" x 1/2" 1/2" - 200m
2	Blocky	12" x 24" 1" - 100m	Coarse Granular	1" x 2" 1/2" - 200m	1" x 2" 1/2" - 200m	1/2" x 1" 1/2" - 200m
3	Blocky	12" x 12" 1/2" - 100m	Coarse Foliated	2" x 2" 1" - 200m	2" x 2" 1" - 200m	1" x 1" 1" - 200m
4	Slabby	6" x 18" 1/4" - 100m	Coarse Tabular	1" x 4" 3/4" - 200m	1" x 4" 3/4" - 200m	1/2" x 1" 1/2" - 200m
5	Boulders	6" x 6" 1" - 100m	Coarse Granular	3" x 3" 1" - 200m	3" x 3" 1" - 200m	1" x 1" 1/2" - 200m
6	Pebbles Cohesive	3" x 3" 1/2" - 100m	Pebbly Cohesive	1" x 1" 1/4" - 200m	1" x 1" 1/4" - 200m	1/2" x 1/2" 1/4" - 200m
7	Muddy Cohesive	1" x 12" 50m - 200m	Muddy Cohesive	1/2" x 1/2" 35m - 200m	1/2"x1/2" 35m - 200m	1/4"x1/4" 35m - 200m

Note: (a) Top: Maximum Size
(b) Bottom: Size Range over 60%

(b) Sizes for hydraulically excavated is unknown but assumed to be same as mechanically excavated.
(c) Assumed to be 25% to 50% less than mechanically excavated for middle range.

FIGURE 7-2

MUCK CHARACTERISTICS

After establishing the RQD and correlating the other information available from USGS maps, this information was used to try to predict the size gradation and general characteristics of the muck that would be produced from the various means of rock breaking which might be employed. Seven classifications of the type of muck were chosen based upon characteristics which might be most useful to determine the kind of transport and handling that would be the most efficient.

It is not proposed that the numbers assigned are correct or can be used for engineering design, but they are presented to represent a qualitative approach to solving the complicated problems associated with developing a meaningful interpretation of the heterogeneous rock qualities. They are only proposed as guidelines which, with sufficient research and study, might be correlated and refined to result in quantitative values.

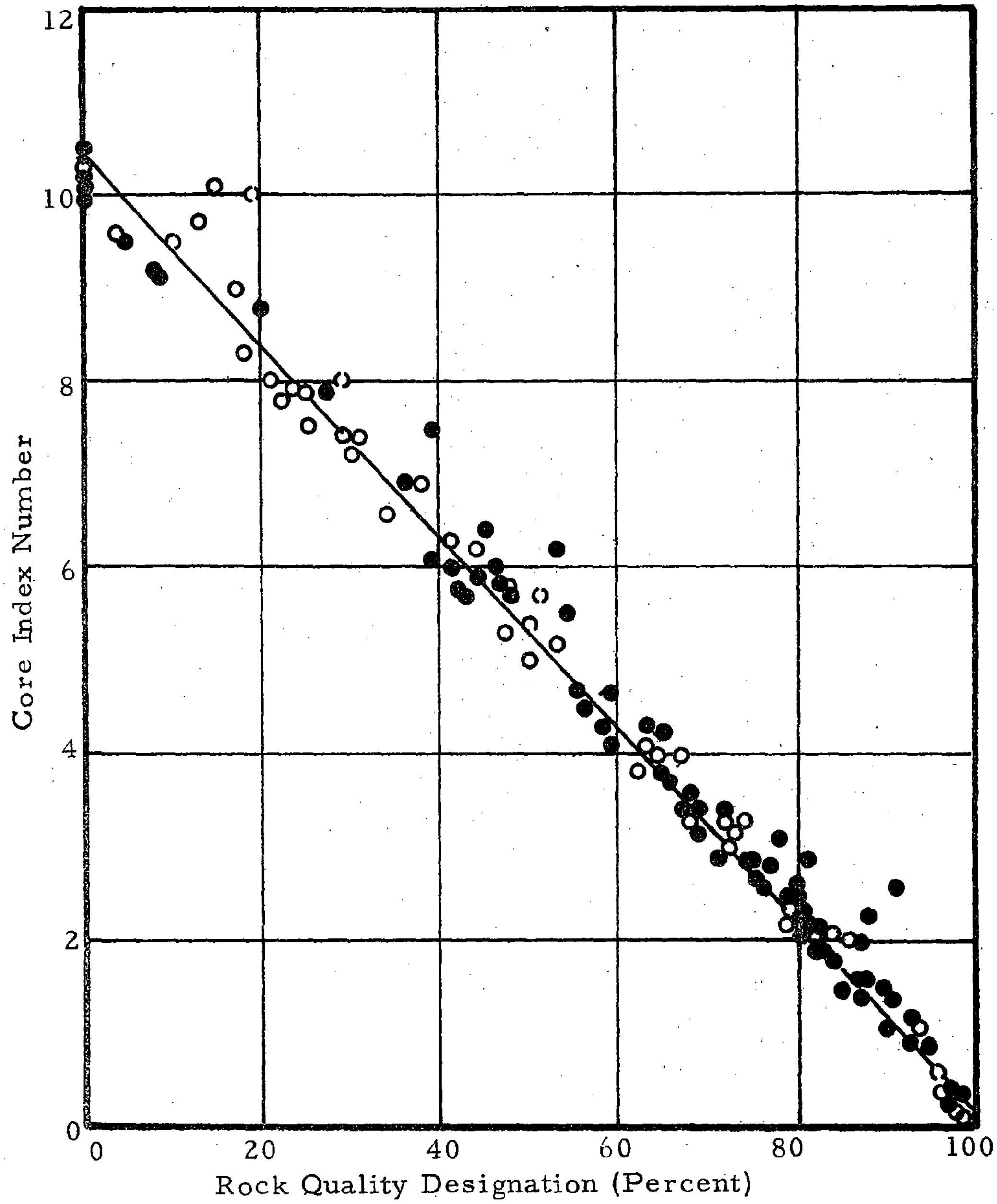
Before attempting to explain the thought process in developing the MDN, an explanation of the RQD and the relationship with the rock engineering properties is necessary.

Deere, et al,[4, 5] have shown through computer analysis a high degree of correlation among the various physical properties and among physical and elastic properties. They have also compared the static and dynamic properties from exhaustive testing and data as developed by the U. S. Bureau of Mines, Bureau of Reclamation, and others.[6]

As a result of these investigations, Deere has proposed categorizing rocks by a method designated as RQD developed at the University of Illinois. It is a modified core recovery classification that is based on counting only those pieces of sound rock in the core which are longer than 4 inches. This eliminates some uncertainties and partially reflects the degree of weathering and other weakness factors. This basic RQD is correlated with velocity index and a qualitative description of rock properties as shown in Table 7-1.

More or less contemporary with the development of the RQD by Deere, J. R. Ege of the U. S. Geological Survey proposed a core index number to assist in categorizing rock types in an effort to predict the behavior of tunnels at the Nevada Test Site. As defined by Ege (1967), the core index number is the sum of "the 0.1 percent core loss, 0.1 percent broken core (less than 3-inch pieces), and joint frequency." Both Ege and Merritt (1968) have shown that there is a nearly perfect correlation between RQD and the core index number for a given site, indicating that they can be used interchangeably.* Figures 7-3 and 7-4 show the correlations obtained.

*Preceding paragraph paraphrased from Reference 1, page 139.

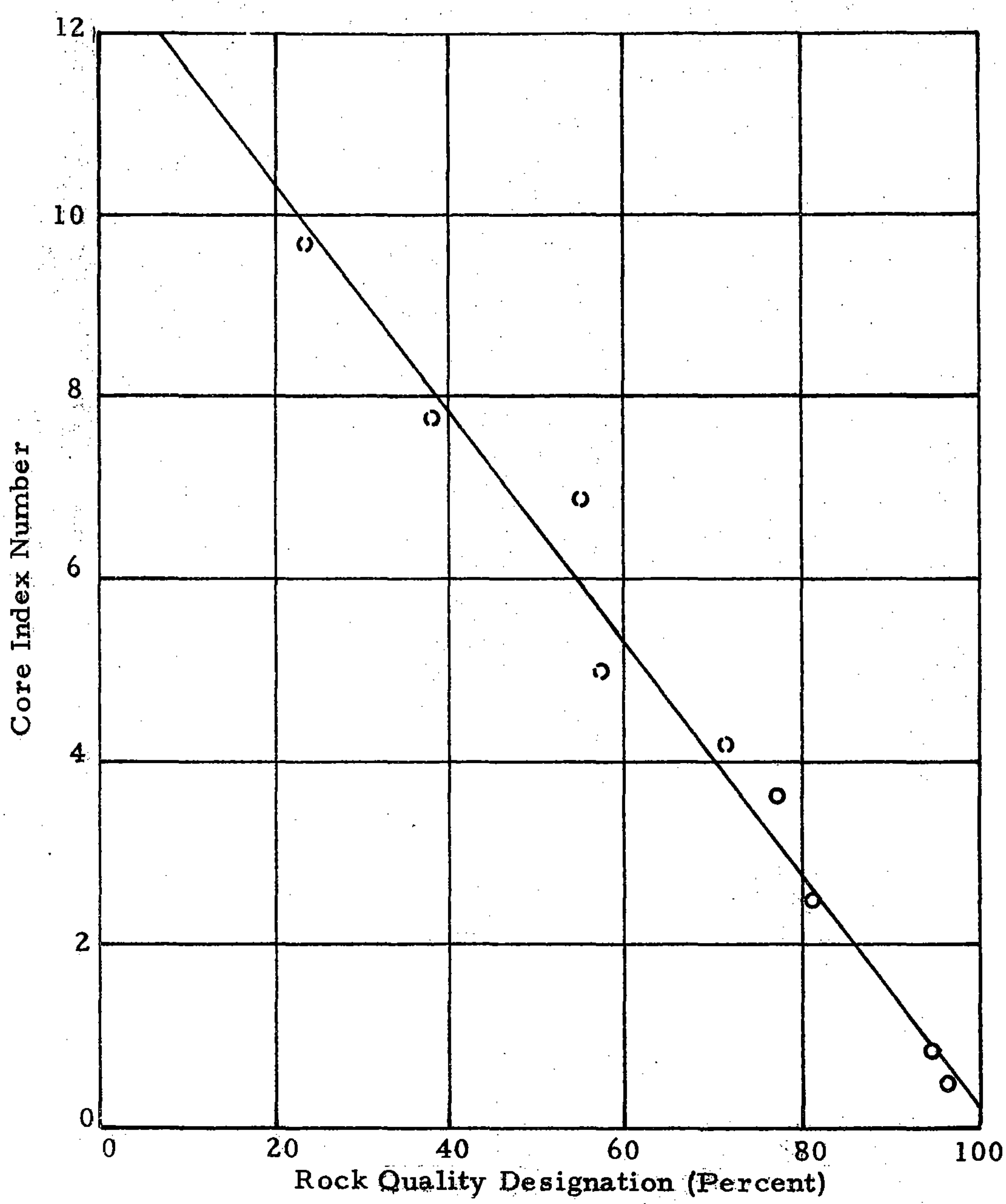


LEGEND

- ● Nevada Test Site - Dacite and Rhyolite
- ○ Tehachapi Pumping Plant Site - Gneiss

FIGURE 7-3

RELATIONSHIP BETWEEN ROCK QUALITY DESIGNATION AND CORE INDEX NUMBER
(After Merritt, 1968)[1]



LEGEND

○ Nevada Test Site Rocks

FIGURE 7-4

CORRELATION OF ROCK QUALITY DESIGNATION AND CORE INDEX NUMBER
(After Edge, 1967)[1]

TABLE 7-1

RQD AS AN INDEX OF ROCK QUALITY
After Deere, et al(4)

RQD (Percent)	Velocity Index	Description of Rock Quality
0-25	0 to 0.20	Very Poor
25-50	0.20 to 0.40	Poor
50-75	0.40 to 0.60	Fair
75-90	0.60 to 0.80	Good
90-100	0.80 to 1.00	Excellent

Velocity Index = $(V_F/V_L)^2$

V_F = field seismic velocity

V_L = laboratory sonic velocity

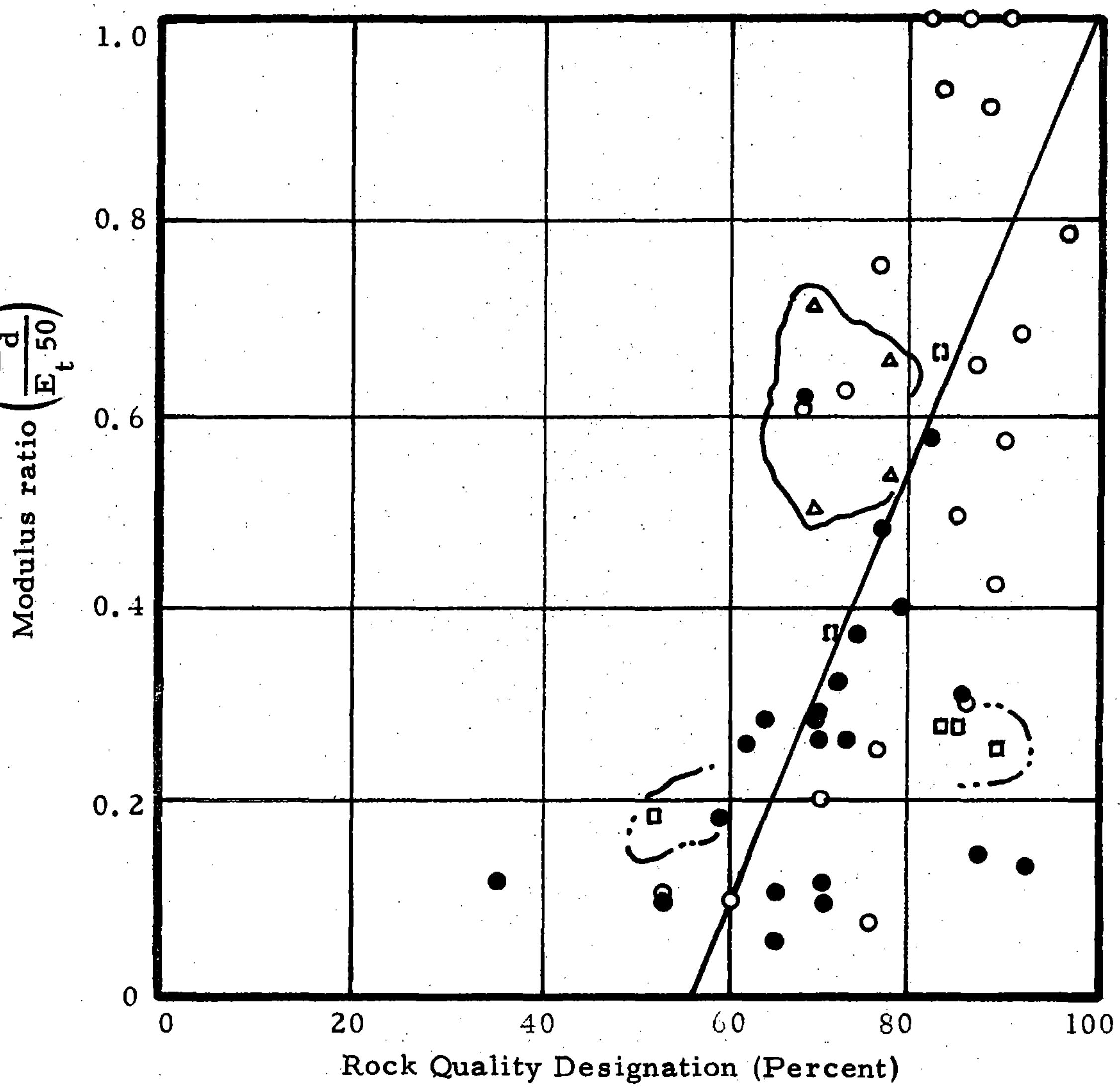
Other investigations have indicated that the RQD can be correlated with some of the properties of a rock mass. Merritt (1968) reported data indicating that:

1. There is a direct correlation between the RQD and rock mass permeability.

2. The electrical resistivity tends to increase with the RQD, but data is very scattered.*

Coon (1968)(4) reported that the RQD can be related to four modulus ratios, E_c/E_{t50}, E_d/E_{dyn}, E_e/E_{t50}, and E_e/E_{dyn}, where E_d and E_e are the modulus of deformation and modulus of elasticity, respectively, for the in-situ static test; and E_{dyn} and E_{t50} are the laboratory dynamic and static moduli. Figure 7-5 is typical of the data presented by Coon. He also presents data, shown in Table 7-2, that indicates some correlation between the RQD and both the rate of tunnel advance and the supports used.

*Preceding paragraph paraphrased from Reference 1, page 139.



LEGEND

- ● Dworshak Dam, Granite Gneiss, Surface Gages
- ○ Dworshak Dam, Granite Gneiss, Buried Gages
- □ Two Forks Dam Site Gneiss
- ⊏⊐ Yellowtail Dam, Limestone
- △ Glen Canyon Dam, Sandstone

FIGURE 7-5

VARIATION OF MODULUS RATIO WITH ROCK QUALITY DESIGNATION

(After Deere, et al)[4]

TABLE 7-2

CORRELATION OF RQD WITH TUNNEL SUPPORT REQUIREMENTS AND ADVANCE RATE

After Coon (1968)[5]

RQD	Support Requirement			Advance Ratio = Predicted Rate / Rate in Best Rock
	Width of Opening			
	10 feet	25 feet	50 feet	
90-100	Minimum	Minimum to Intermediate	Intermediate to Maximum	0.8 - 1.0
75-90	Minimum to Intermediate	Intermediate	Maximum	0.5 - 0.8
50-75	Intermediate to Maximum	Maximum	Maximum	0.2 - 0.6*
25-50	Maximum	Maximum	Maximum	0.1 - 0.3*
0-25	Maximum	Maximum	Maximum	>0.1*

*Estimated:

Minimum Support - Unsupported or Occasional Rock Bolts

Intermediate Support - Light Steel or Pattern Rock Bolts

Maximum Support - Heavy Steel or Pattern Rock Bolts (Long Bolts, Mesh)

Relationship of Muck, Hardness, and Abrasiveness

The hardness of a rock is a property that has not been universally defined or quantified. In a broad sense, hardness can be defined as the resistance of a rock to penetration. The three common methods for measuring rock hardness involve different concepts of hardness; for example, resistance to scratching (Moh hardness, Figure 7-6); impact rebound characteristics (scleroscope hardness); and crushing resistance (Protodyakonov hardness). The Rockwell and Brinell hardness tests, commonly employed for metals, are not well suited for use on rocks due to their brittleness.

Moh Hardness - The scale of hardness used to designate the relative hardness of minerals is based on the resistance which a smooth surface of the mineral offers to scratching. The degree of hardness is based on the relative ease or difficulty with which one mineral is scratched by another, or by some other convenient material such as a pocket knife blade or fingernail. It is designed by numbers ranging from 1 to 10; the basic minerals arranged in order of increasing hardness are:

1. Talc
2. Gypsum
3. Calcite
4. Fluorite
5. Apatite
6. Orthoclase
7. Quartz
8. Topaz
9. Corundum
10. Diamond

Each of these minerals will scratch those lower on the scale and will be scratched by those higher on the scale. The intervals between minerals on the scale are roughly equal except between corundum and diamond where the interval is substantially larger. Hurlbut[7] references one investigation (Figure 7-6) which showed that if quartz has an absolute hardness of 7 and corundum 9, the hardness of diamond would be 42.4.

General correlations between hardness and crystal structure have been established. Hardness is generally greater when the valence of the atoms and the packing density are high. Since crystals are composed of an ordered array of atoms, hardness often varies with crystallographic direction; and, consequently, in the massive rock it can establish planes of strength and weakness in relation to the crystallographic orientation.

The hardness of a rock composed of several different minerals is a function of the hardnesses of the constituent minerals. For coarse-grained rocks, Moh hardness is normally stated in terms of the hardnesses of the constituent minerals. In fine-grained rocks, it reduces to a measure of the average resistance to scratching.

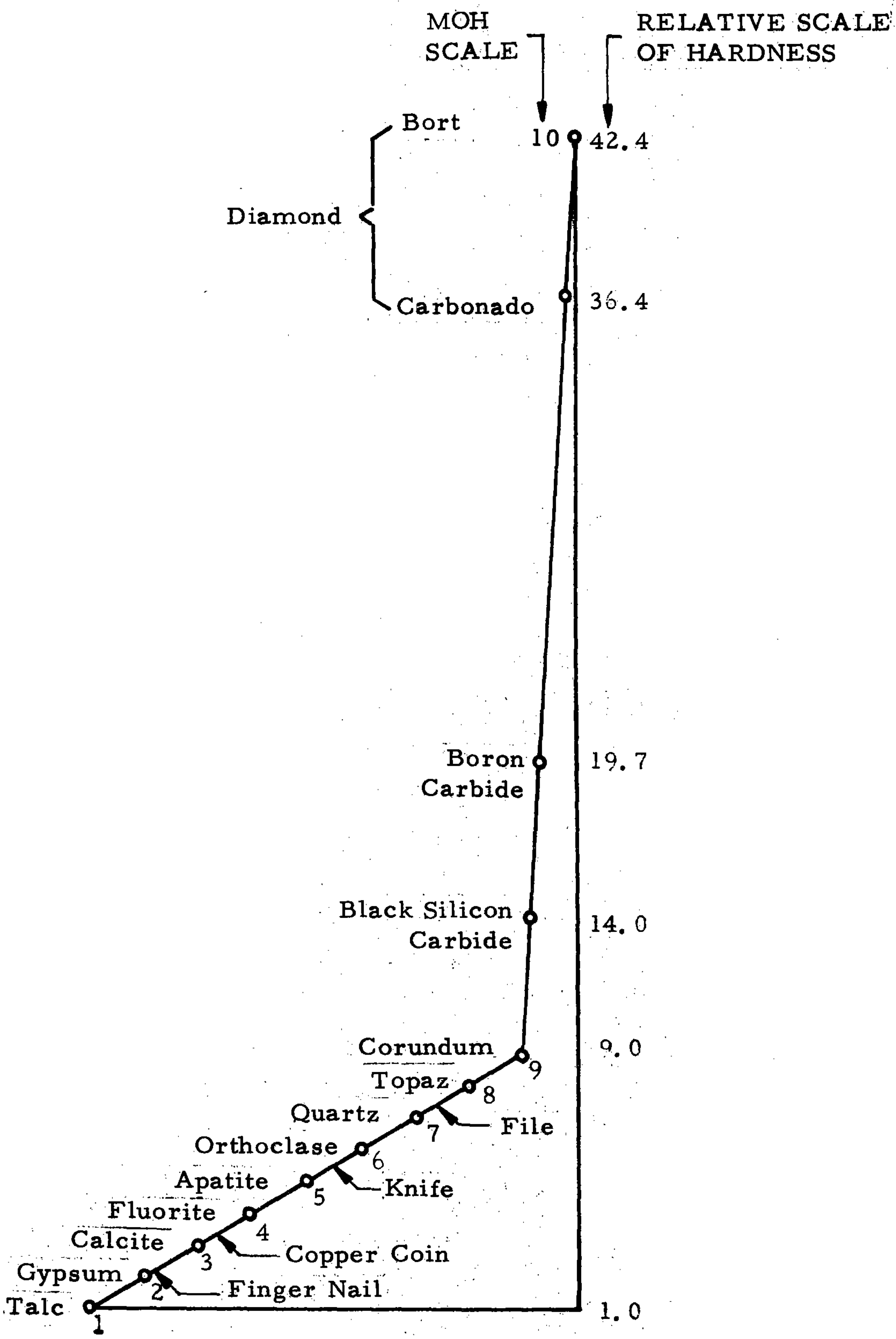


FIGURE 7-6

RELATIVE HARDNESS OF MINERALS
IN THE MOH SCALE OF HARDNESS
After Hurlbut[7]

Scleroscope Hardness - Scleroscope hardness is a measure of the impact rebound characteristics of a material. The Shore scleroscope, as described by Small,[8] is the most commonly used instrument. It allows a standard indentor to fall from a fixed height onto the surface of the material. A small indentation caused by the impact is made on the surface, and the rebound height is the measure of hardness.

Since the Shore scleroscope measures the hardness over a small area of impact, the reading may depend on which mineral grain is struck. For example, in a coarse-grained granite the reading obtained from a quartz grain would be much higher than one from a mica grain; while in a fine-grained rock, the consistency of the results would be more a function of gross homogeneity. Consequently, test results are normally stated in terms of both the average reading and the standard deviation.

In addition to the inherent error in the test procedure, care must be taken to hold other physical effects constant. The U. S. Bureau of Mines[9] found that moisture content affected Shore scleroscope readings on limestone and sandstone. The readings in the oven-dried state were as much as 20 percent higher than the air-dried state, and in the saturated condition they were 10 percent lower than when air-dried. No moisture effect was noted, however, on a dolomitic marble, granite, and another sandstone.

Protodyakonov Hardness - The Protodyakonov hardness sometimes used as a measure of rock strength in drillability and comminution studies was developed by the Russian Professor M. M. Protodyakonov.[10] The basic procedures in this determination are:

1. Each sample is broken with a hammer and five test specimens randomly chosen, each being 20 to 40 millimeters in size with a total volume of 10 to 20 cubic centimeters.

2. The test specimens are individually placed in a tubular drop tester and are impacted with a 2.4-kilogram drop weight falling from a height of 60 centimeters. The number of impacts, n, of the drop weight may be varied from 5 to 15, but must be the same for each test specimen.

3. The broken material from the five test specimens is then sieved together on a 0.5-millimeter wire screen.

4. Fines which pass the 0.5-millimeter screen are then poured into the tube of the volumeter, and the height of the dust is recorded.

5. The strength coefficient, f, is then given by the equation:

$$f \cong \frac{20n}{L}$$

where n = number of blows and L = height of column in millimeters.

Again, in addition to the inherent error in the test procedure, it has been established that the measured hardness is affected by the size of the sample taken, the number of blows, screening time, and the compaction in the volumeter. By closer control, the results are more consistent, and it has been further established that the strength coefficient is empirically related to the strain energy in uniaxial compression at failure, by the equation

$$A \cong 0.53f$$

where

$A = (\sigma_c)^2/(2E)$ kg cm/cm^3

σ_c = uniaxial compressive strength

E = Young's modulus of elasticity.

Protodyakonov states further that the Shore scleroscope hardness, h, is related to Young's modulus E by

$$E \cong 1.07 \times 10^6 \frac{h}{154 - h} \text{ kg/cm}^2 .$$

It should be noted that this test is in effect a strength or toughness test and probably gives some of the best information as to how a rock can be expected to behave when blasted or fragmented with a crusher or a mechanical excavator. Consequently, it would give valuable information in relation to the type and size distribution of muck to be expected from a given excavation process; for example, the height of the dust recorded when material is poured into the volumeter indicates the quantity of very fine material produced and is a very important factor when considering the use of hydraulic transport.

There are several other methods of testing the hardness of rocks; and because of the heterogenetic characteristics of rock, it is impossible to state which is the best. The end use of the data must be considered, and the method chosen which best suits the determination of the specific qualities required.

Considerable testing and research has been done by Deere and Miller[4] relating the hardness to rock characteristics. Three methods of testing hardness were employed on the specimens; namely, (a) Shore hardness, (b) Schmidt hardness, and (c) abrasion hardness.

Since both the Shore hardness and Schmidt hardness are based upon readings from the impact and rebound from a hammer blow, they are probably more indicative of rock characteristics associated with drilling or blasting. The new abrasion hardness test, on the other hand, employs the use of a high speed dental carbon disc in direct contact with the specimen and rotating with a measured applied load and duration time. This may be more accurately indicative of the characteristics of the resultant muck from either blasting, mechanical breaking, or other present experimental processes.

Soft, highly weathered rocks or portions of the rock mass such as cements or intergranular bond (or lack of bond) are apparent with the abrasion test. Also, larger grained rocks depart from a straight-line relationship more than the fine-grained. Fine-grained rocks such as quartzites, although welded but containing numerous bedding planes and intermittent microcracks, show lower abrasion hardness than the average of their mineral constituents.

The test results were measured by means of an Ames dial comparator using a specially built foot, which was the exact size of the carborundum abrasion disc. Areas of the circle segments cut were computed and averaged to obtain an abrasion resistance number. As the softer rocks had deeper cuts, the abrasion hardness number was reported as the reciprocal of the computed area cut.

Abrasiveness - The abrasiveness of a rock, like hardness, is a property which is not easily defined in terms of a fundamental unit of measure. Relative abrasiveness of various rocks is normally determined with some type of standardized equipment and the abrasive index of a rock is stated as some number which is a function of the rock and type of equipment.

Abrasiveness is a particularly important rock property in comminution and particularly in rock handling processes, since it governs the wear on the equipment. The abrasive action of rocks is not easy to predict since rocks of the same structural geological classification may vary widely in abrasiveness from one locality to another, and sometimes even between two points in close vicinity.

Three types of equipment for measuring abrasiveness are commonly used: The Dorry abrasive hardness tester, the paddle-type machine, and the Los Angeles machine.

Dorry Abrasive Hardness Tester - This apparatus was developed by the French School of Bridges and Roads and used on rock by the U. S. Bureau of Mines.(9) A cylindrical rock specimen is abraded against a steel disc rotating at a specified rate of revolution for a given number of revolutions. An abrasive powder is applied to the disc during the test. The weight of the material abraded from the test specimen is determined and used in equations which are arbitrarily specified for the particular values of the system variables employed.

Paddle-Type Machine - This machine was developed by the Pennsylvania Crusher Division of Bath Iron Works Corporation.(12) A 400-gram charge of broken rock passing 0.742 and retained on 0.371 Tyler standard screens is placed in a 12-3/16 inside diameter drum rotating at 74 revolutions per minute. A standard paddle 1 inch wide, 3 inches long, and 1/4 inch thick rotates within the drum at 632 revolutions per minute in the opposite direction to the drum. Four 400-gram samples are run, each for 15 minutes. The paddle is accurately weighed before and after the four tests with the loss in weight of the paddle in tenths of a milligram representing the abrasive action for a particular rock. A new paddle surface is required for each group of four runs since work-hardening occurs, especially in the first 400-gram run. All paddles for a given series of tests must be made of the same steel and of the same hardness so that all measurements will have the same base.

Los Angeles Machine - The design of the Los Angeles abrasion testing machine and the procedures for its use on coarse aggregate are specified by the American Society for Testing and Materials (ASTM Designations C 131-66 and C 535-65). A specified charge is introduced into a standard rotating drum having a shelf attached to the inside. The charge consists of specified weights of the rock in certain size ranges and a specified number of standard steel balls. The drum is rotated at 30 to 33 revolutions per minute for a specified number of revolutions. The abrasiveness is then taken as the percent loss in weight of the test sample with everything finer than a number 12 sieve considered as loss.

To summarize the usefulness of the abrasion hardness tests, the amount of weathering, bedding planes, soft intergranular bond, and microcracks is extremely important in determining the expected fragmentation characteristics of a rock. Rocks which exhibit a large percentage of such defects as determined by the abrasion hardness test method can be expected to break more readily and into smaller fragments.

Relationship of Muck and Drillability

The relationship of rock drillability to muck is an area which cannot be readily correlated with the type of muck to be expected from any given rock. This is largely attributable to the fact that the rock drillability itself is governed to a large extent by the successful application of rock drills. This is true whether the drilling is done with rotary or percussive types. The many variables involved complicate the interpretation of the specific energy required to drill any given rock stratum. Also, the word "hardness" in the drilling industry has several meanings, depending upon the drilling method employed. For example, any rock which is difficult to drill with a rotary bit is usually termed "hard rock." With percussive drilling, "hard rock" is any rock which is difficult to penetrate or chip; while in diamond drilling, the term is used for highly abrasive rock which causes excessive wear on the bit.

There has been extensive research conducted by manufacturers which was primarily oriented toward their manufactured products such as drill rigs, drill steel, bits, and other equipment. However, very little basic research has been accomplished relative to the basic aspects of "drillability" and its relationship to the physical properties of rock. The more recent work done in this field is described in Reference 10. Briefly, the use of the microbit (1-1/2-inch diameter) and its correlation to drillability for much larger sizes has been one of the main contributions. As the use of the microbit involves all three types of tests (i.e., hardness, abrasion indentation, and dynamic or impact) this probably accounts for its more consistent and usable test results.

Relationship of Muck and Compressive Strength

Probably the most widely used measurement of the physical properties of rock is uniaxial compressive strength. It has been investigated more than any other property; and a wealth of data relative to test procedure and interpretation of results is available.

Basically the uniaxial compressive strength is determined by loading cylindrical or prismatic specimens in axial compression until failure. The testing machine is normally equipped with a spherical compression head to assure uniform loading across the ends of the test specimen. The results can be affected by a number of factors, but the most significant are the smooth end surfaces of the specimen and the alignment of the end plates. The compressive strength σ_c is calculated from the equation

$$\sigma_c = \frac{P}{A}$$

where

P = load at failure, and

A = cross-sectional area of specimen.

A standardized method of test for compressive strength of natural building stone was published by ASTM in 1941.(11) To eliminate column effects, early testing was performed on specimens having length to diameter (or lateral dimension) ratios (L/d) of approximately 1:1. If the L/d ratio was not 1:1, the strength of an equivalent cubical specimen σ_c was to be calculated from the empirical equation

$$\sigma_c = \frac{\sigma_p}{0.778 + 0.222\left(\frac{d}{L}\right)}$$

where

σ_p = compressive strength of specimen having a height greater than the lateral dimensions,

d = diameter or minimum lateral dimension normal to stress, and

L = length of specimen along line of compression.

Obert, Windes, and Duval(9) verified the above equation for L/d values ranging from 0.5 to 1.5. Figure 7-7 shows excellent agreement between the curve calculated from the empirical equation and experimental points representing the average for six different rocks.

As previously stated, the compressive strength values are also influenced by the end conditions of the test specimen and the loading mechanism. A swivel loading head is usually employed so that it will better adjust to the specimen and provide a more uniform load.

The United States Bureau of Mines(13) has recently investigated the effects of end conditions of the test specimen and machine variables on compressive strength for four rock types. They conclude that surface irregularities should not vary from a plane surface by more than

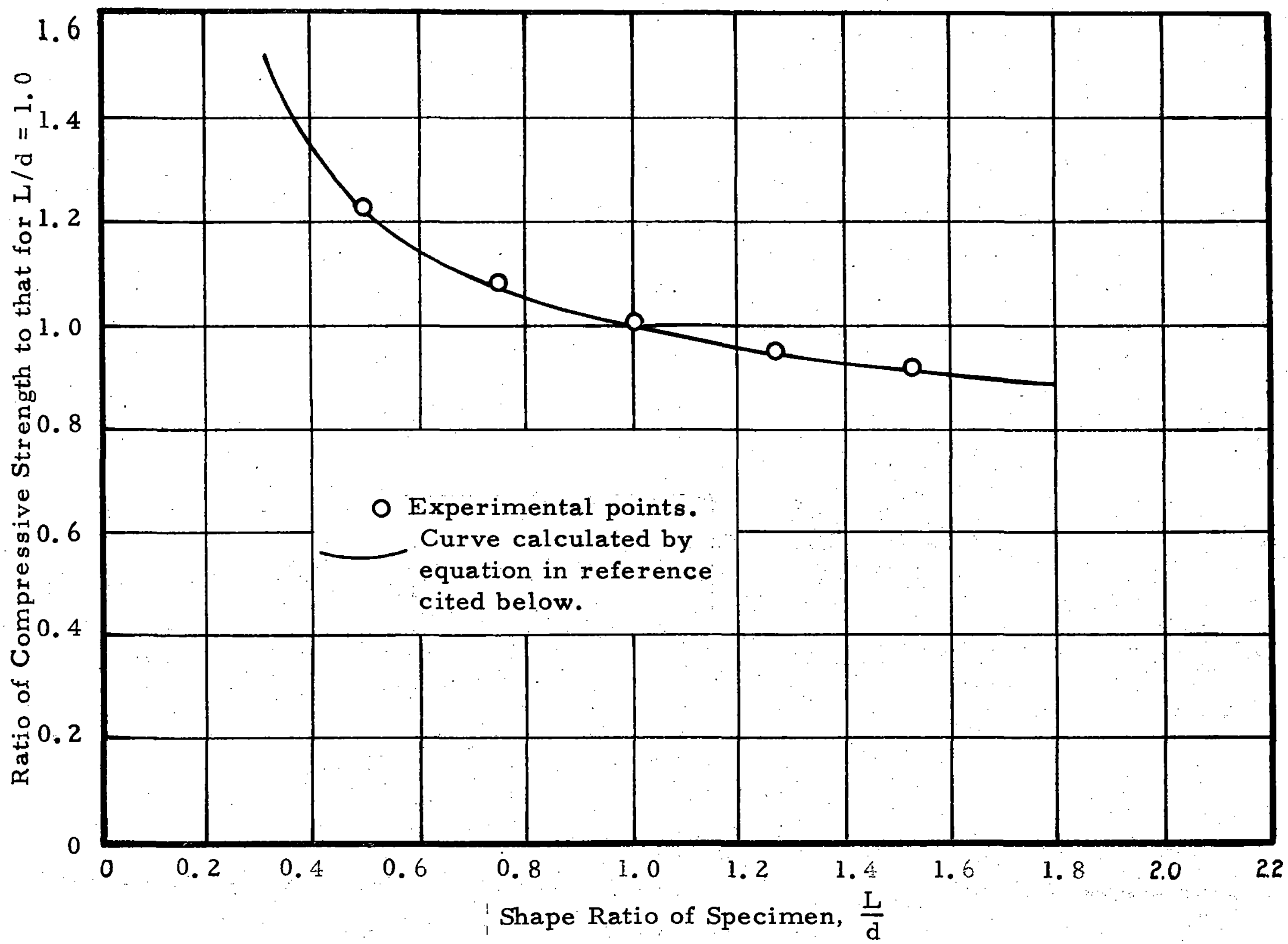


FIGURE 7-7

SHAPE RATIO VERSUS COMPRESSIVE STRENGTH
After Obert, Windes, and Duvall(9)

0.001 inch. Also, nonparallelism of the specimen ends should not exceed 8 minutes for a rigid loading head or 15 minutes for an adjusting head. The diameter and thickness of the loading platens did not affect the strengths statistically.

MUCKABILITY DESIGNATION NUMBER

Lithology - Relationship of Rock Type and Muck

Lithology is the study of the rock character and describes in detail the mineralogy, texture, and fabric along with a descriptive geological name. Such descriptions of the rock are very meaningful to the person familiar with geologic terms; however, there is a degree of ambiguity in relation to engineering properties.

For example, the uniaxial compressive strength of a limestone may range from 5,000 to 35,000 pounds per square inch. Sandstone may also vary over a wide range depending on the type and degree of cementation. On the other hand, a quartzite usually is quite constant in hardness. It is therefore evident that for a meaningful description of a rock, both the geological and engineering description is necessary.

In addition, the lithology by means of the geologic name indicates the association between certain rock types and other in-situ features that should be anticipated. As an example, the occurrence of limestone, gypsum, or rock salt would alert the investigator to look for solution-enlarged fissures such as caves and sink holes. Lava flows would indicate the possible presence of columnar jointing. Both of these examples would in turn alert the tunnel designer to anticipate large bodies of perched water in the first case and considerably blocky ground for muck handling in the second case.

These examples illustrate the methodology and thinking used in classifying the muck types in relation to the lithology.

Uniaxial Compressive Strength and Young's Modulus as Related to Rock Characteristics

The classification of a compressive strength and Young's modulus as performed from laboratory testing refers to intact rock. Intact rock is the rock material or substance which can be sampled and tested in the laboratory. It must be free of larger scale structural features such as joints, bedding planes, partings, and shear zones. Considerable work has been done on the classification by Coates,[14] Parsons,[15] and Miller.[16]

The bases for the classification are the two important engineering properties, uniaxial compressive strength and the modulus of elasticity, both of which have been supplied by the USGS[2] for the proposed Northeast Corridor routes. The compressive strengths and modulus of elasticity in Table 7-3 were assigned from USGS data.

The modulus ratio was calculated by the equation

$$\text{Modulus Ratio} = E_{t/\sigma a\,(ult.)}$$

where

E_t = tangent modulus at 50 percent ultimate strength, and

σa (ult.) = uniaxial compressive strength.

Making use of all three of these relationships and "backing in," so to speak, the RQD was arrived at for each type of rock (see Reference 3).

Having arrived at the RQD and knowing the uniaxial compressive strengths, values of the modulus of elasticity, and the calculated modulus ratio, it then became possible to combine this information along with the lithology to assign an arbitrary number. This arbitrary number, from 1 to 7, was assigned largely by inspection but consistent with the above criteria.

By this correlation with the RQD, it then becomes possible to extrapolate other relationships from the wealth of research work done by Deere, Merritt, and Coon;[5] the U. S. Bureau of Mines;[9] and others.

It has been shown by Coates[14] that the fracture frequency varies with the RQD (Figure 7-8).

Seismic and Sonic Values as Related to Rock Classification

The effect of discontinuities in the rock mass have been shown by Deere.[4] These discontinuities affect the in-situ compressional (seismic) wave velocities and when compared with the laboratory sonic velocity of an intact core obtained from the same rock mass as shown in Figure 7-9, the discontinuities are evidenced by the decrease in the compressional wave velocities which causes a decrease in the ratio

$$V_F/V_L$$

where

V_F = the compressional wave velocity of the rock mass in-situ

V_L = the sonic velocity of the intact specimen.

TABLE 7-3

NORTHEAST CORRIDOR ROCK - ASSIGNED MDN

Map Unit Number	Average Compressive Strength x 10^3	Average Modulus of Elasticity x 10^6	Average Modulus Ratio	MDN (Muckability Designation Number)	Average Compressive Strength	Average Modulus of Elasticity	Average Modulus Ratio
1	15	8	530				
2	30	14	390				
3	18	8	445				
4	30	14	396				
5(2)	30	14	215	1	25	11.0	440
6(2)	18-30	12	220				
7(1)(5)	4-30	5.5	305				
8	18	8	445	2	23	10.0	435
9	18	9	500				
10(2)	30	12	445	3	23	9.8	420
11(3)	9	6	665	4	15.5	7.0	450
12(3)(4)	8	4	500				
13(3)	15	8	530				
14(3)	14	6	430				
15	22	10	455				
16(2)	24-30	12	418				
17(2)	18-30	12	330				
18(4)	8	3.5	435	5	15	6.5	435
19(5)	18	6	330				
20(4)	6	1	125	6	10.5	4.3	430
21(4)	6	1.5	188	7	7.0	3.0	430
22	14	1.5	110				
23	22	10	450				
24	18	2	110				

(1) Tough, hard rock portion is included with MDN Nos. 1 and 2; soft matrix included with MDN No. 7.

(2) Description indicates that harder, dense rocks predominate.

(3) Indication of soft, weathered rocks. They are included with MDN Nos. 5, 6, and 7.

(4) Included in MDN No. 7.

(5) Included in MDN Nos. 2 and 3.

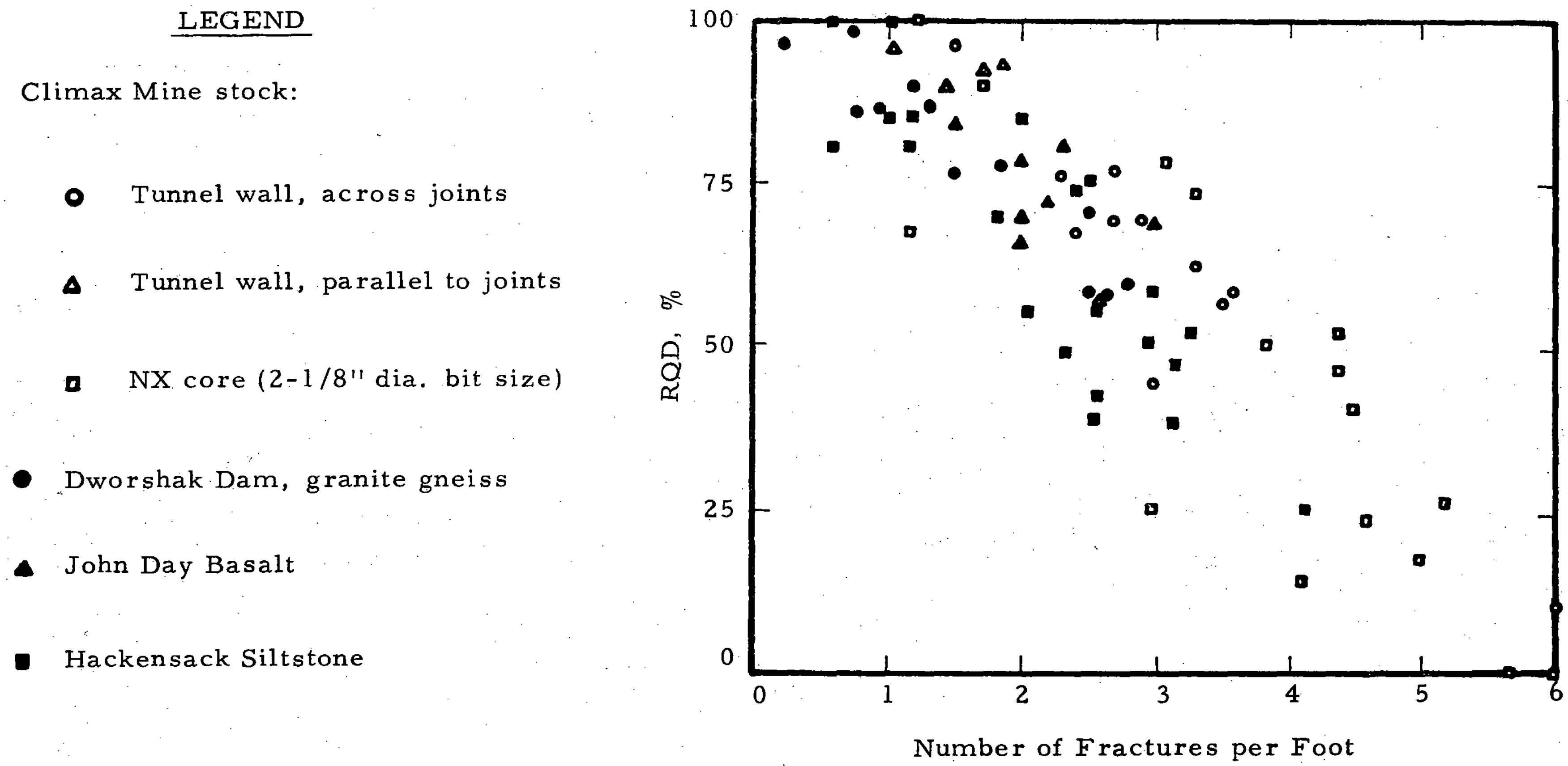


FIGURE 7-8

FRACTURE FREQUENCY, RQD RELATIONSHIP
After Coates (14)

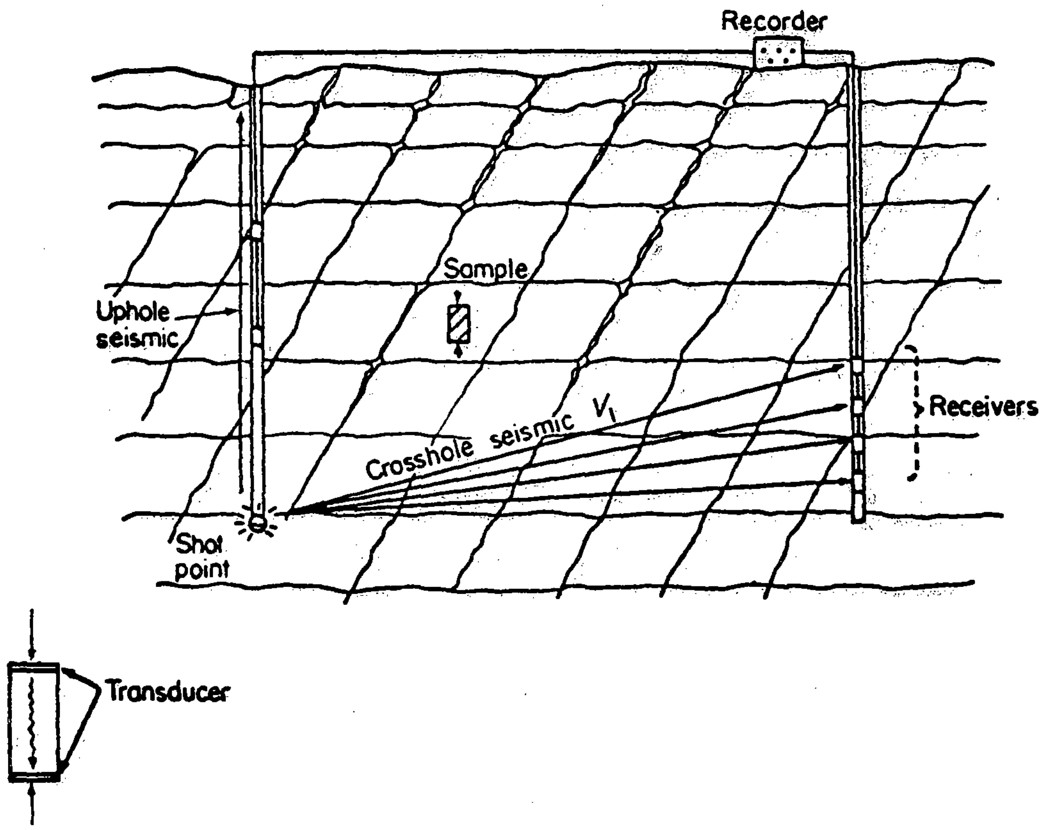


FIGURE 7-9

VELOCITY RATIO DETERMINATION
(Field Measurement and Laboratory Sample)
After Deere, Hendron, Patton, and Cording[17]

As depicted in Figure 7-9, the field seismic velocity is used to determine the variations in the rock mass. It may be measured in three ways: a refraction seismic survey by uphole shooting, by 3-D sonic logging in a drill hole, or from cross hole seismic velocities. Either of these measurements is a quantitative index to the general character of the rock mass.

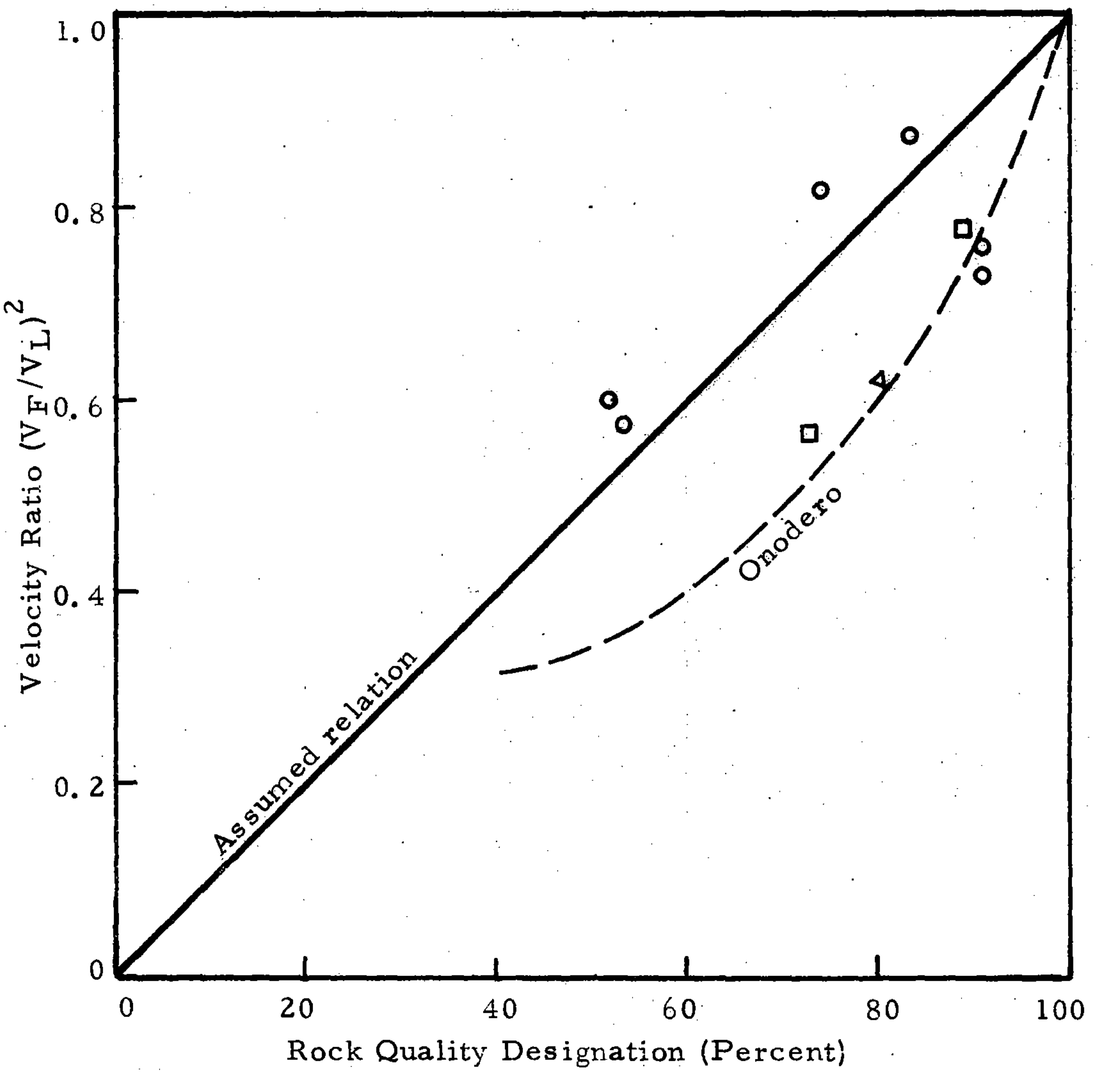
Mainly, the discontinuities or fractures in the rock mass cause an attenuation of the seismic velocity; however, the velocity is also affected by the degree of saturation of the rock mass. When fully saturated, the seismic pulse is coupled across the discontinuities by the water in the openings resulting in an erroneously high reading. Therefore, it is necessary to know the water table, porosity, degree of weathering, and general lithology of the rock mass. It is also important that the intact core sample used for determining the laboratory core velocity is a representative sample of the in-situ rock.

The method of testing is also important. Velocities determined by the resonant frequency technique on an unstressed specimen can be lower than field seismic velocities. This is accountable to the opening of microfractures under the unstressed condition which is not the condition of the rock in place under load from the overlying rock mass and tectonic pressures. Therefore, it is necessary that the laboratory velocity is determined at a stress level high enough to close the microfractures. It is also recommended that the laboratory seismic velocity be determined by the sonic pulse technique since the field measurement is also a pulse velocity measurement.

To summarize, the difference in these two dilatational velocities is caused by the structural discontinuities which exist in the field. This relationship was first proposed as a quality index by Onodera.[18] (See Figure 7-10.)

Upon analyzing these comparisons, it is seen that with the presence of discontinuities the compressional wave velocity, V_F, is lowest in comparison with V_L, the sonic velocity of an intact specimen.

In order to apply these relationships to the data available from the Northeast Corridor rocks, Table 7-3 was compiled to arrive at average values for the geologically distinctive rock types as identified by the USGS map unit numbers. The midpoints of the compressive strength and modulus ranges were used to arrive at the average modulus ratios. After determining the values for the map unit numbers, the rock characteristics from Figure 7-2 were used to assign the distinctive rock types to the corresponding MDN by making use of the concentration of the "rays" depicting the similarity of types and association of characteristics.



LEGEND

- O Manhattan Schist - 6 borings
- □ Rainier Mesa Tuff - averages from two locations
- ◁ Hackensack Siltstone

FIGURE 7-10

VELOCITY RATIO, RQD RELATIONSHIP
After Onodero(18)

When the average modulus ratios and compressive strengths from Table 7-3 are compared with Deere's[4] plotting of these same ranges of values on logarithmic charts (Figures 7-11a through 7-11g), they all fall within the "M" - average modulus range and the rocks would be classified from very high strength down to very low strength by designations AM, BM, EM, and CM with C and D on the border line of CH and DH.

In further search of additional data which would help to determine fractures or discontinuities in a rock mass, it was found that the discrepancy between sonic and static measurements is an indication. The indication is only meaningful, however, when the laboratory sonic determination of Young's modulus and the static modulus are taken at comparable stress levels. The values taken by static techniques are, in general, lower than those obtained by sonic methods. The difference as explained by Zisman[19] and Ide[20] is due to the presence of fractures, cracks, or cavities. Clark[11] observed that the difference in constants may vary as much as 300 percent.

When a stress wave is transmitted by the matrix of a rock and the high frequency components are reflected and refracted from the crevices and cavities, the more compact the rock is the less difference there will be between the static and sonic constants.

According to data compiled by the Bureau of Reclamation,[21] the mean value of Young's modulus in sonic measurement was found to be 10^6 pounds per square inch and the static measurement was 5 by 10^4 pounds per square inch. A longitudinal pulse transmitted across water-filled gaps in concrete, or across a crushed concrete specimen, showed little attenuation of velocity. Therefore, sonic measurements could show a fictitiously high value of modulus for fractured rock. Dvorak[22] showed similar results for a medium under pressure, but the difference did not exceed 50 percent because the cracks and fractures were partially closed.

In summation, based upon assumptions regarding muck characteristics, it can be stated that a definite relationship has been established between the available information of the Northeast Corridor rock strata, the RQD, and the assumed character of the muck to be expected from a given area as designated by the proposed MDN. This relationship is clear, based upon the known compressive strengths and Young's modulus, and it seems reasonable that the same agreement could be established by comparison of sonic and seismic tests if these data were available.

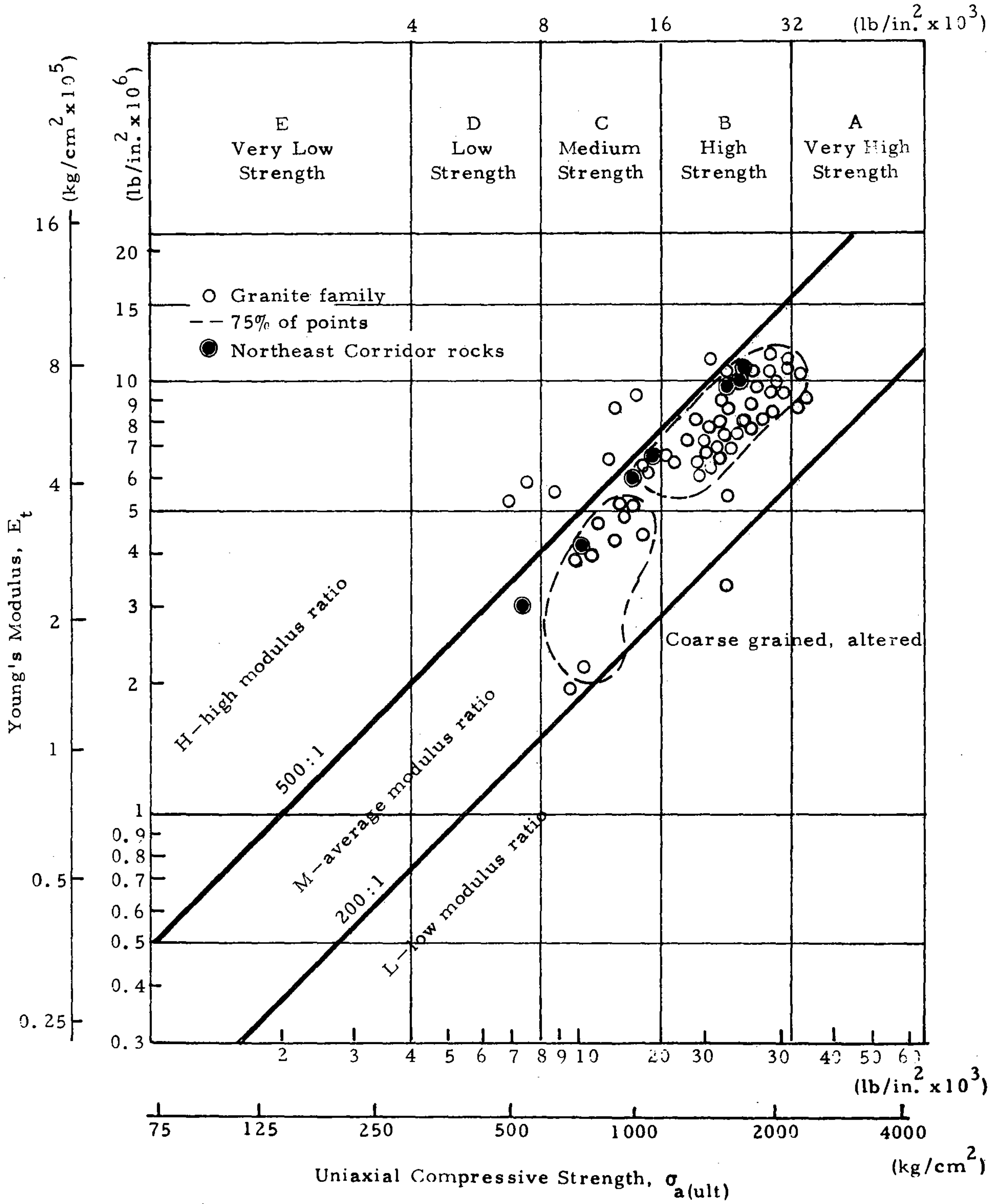
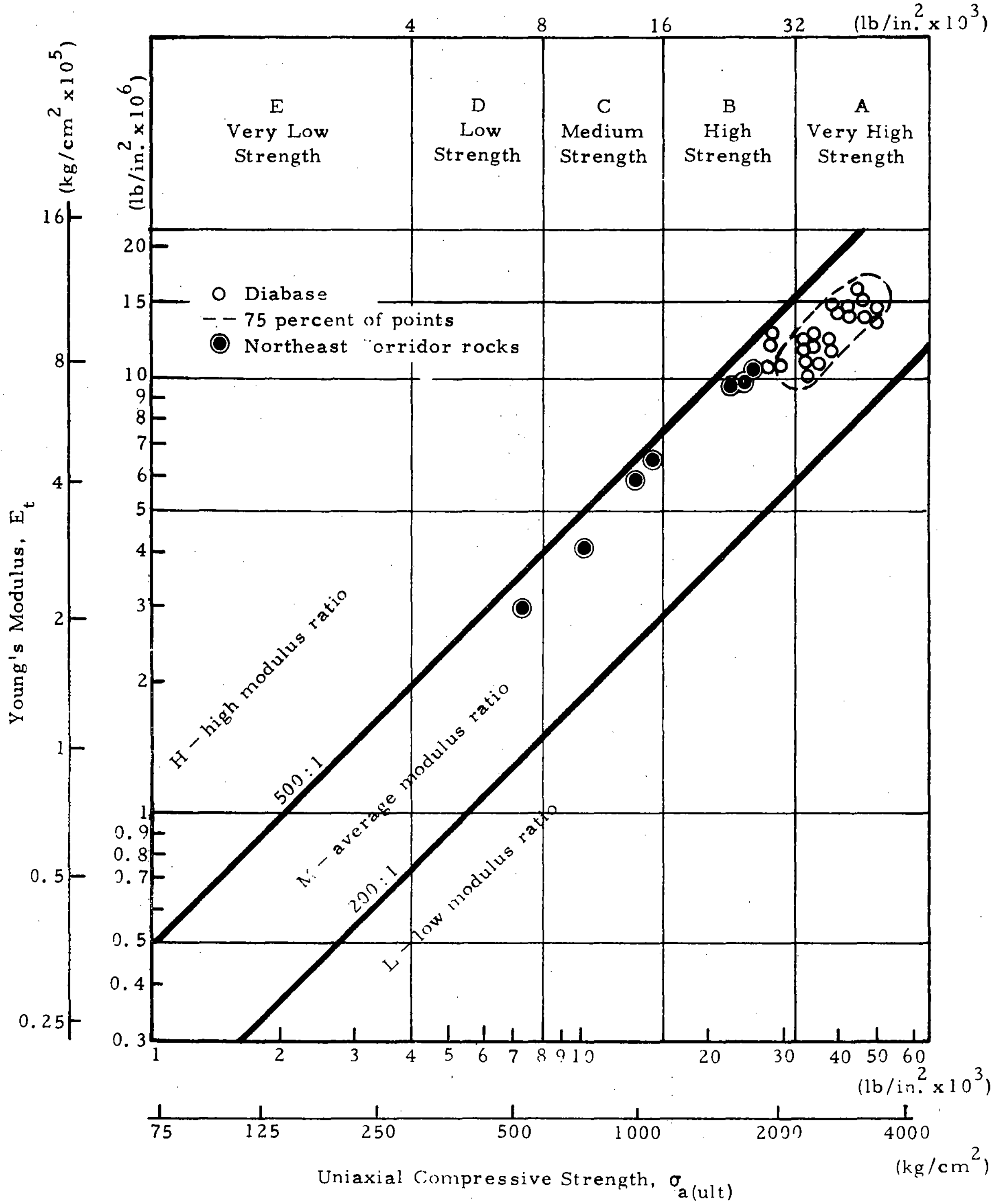


FIGURE 7-11a

COMPRESSIVE STRENGTH, YOUNG'S MODULUS RELATIONSHIP (GRANITE FAMILY)

After Deere, et al(4)



<u>FIGURE 7-11b</u>

<u>COMPRESSIVE STRENGTH, YOUNG'S MODULUS RELATIONSHIP</u>
<u>(DIABASE FAMILY)</u>
After Deere, et al[4]

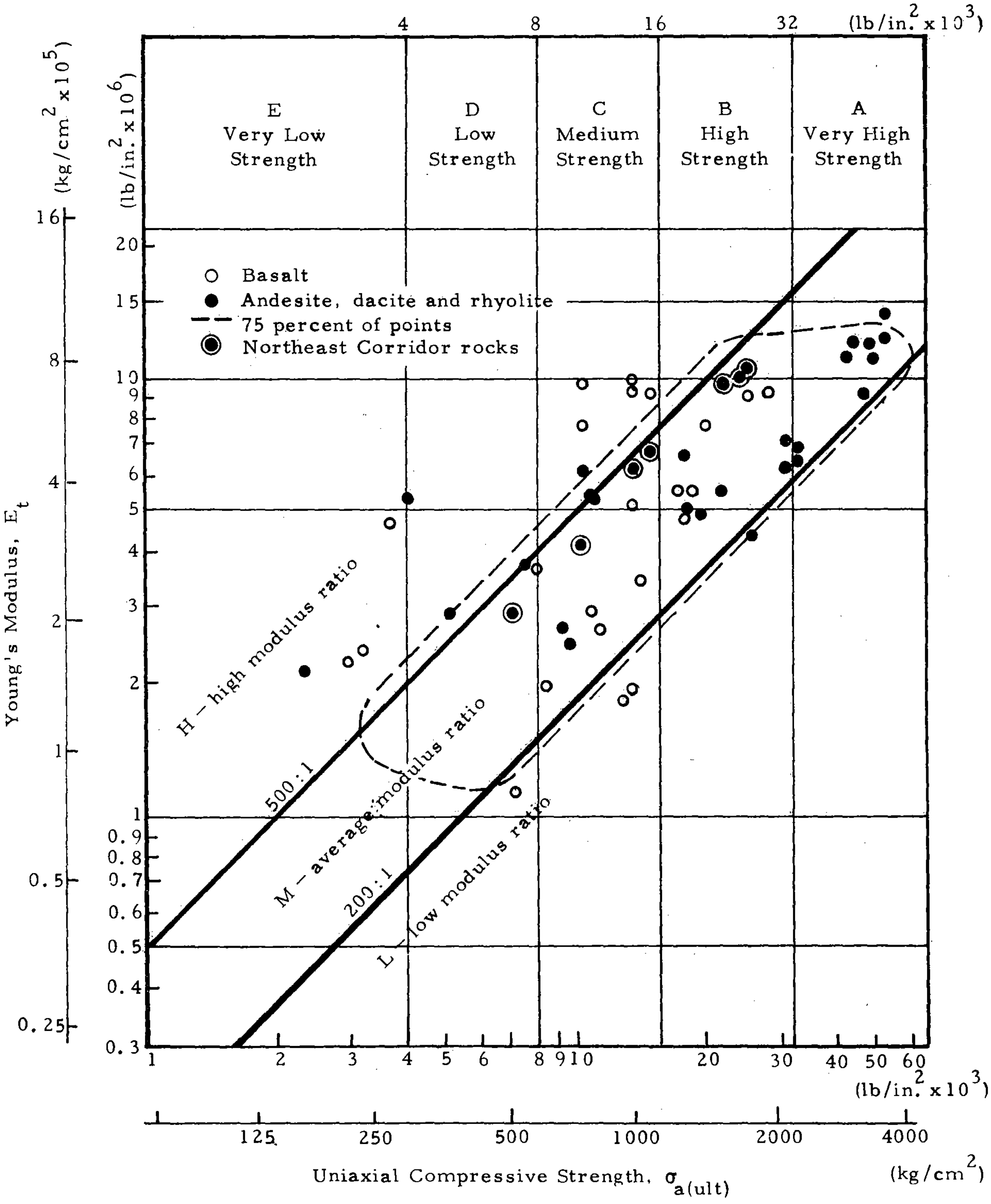


FIGURE 7-11c

COMPRESSIVE STRENGTH, YOUNG'S MODULUS RELATIONSHIP (BASALT FAMILY)

After Deere, et al[4]

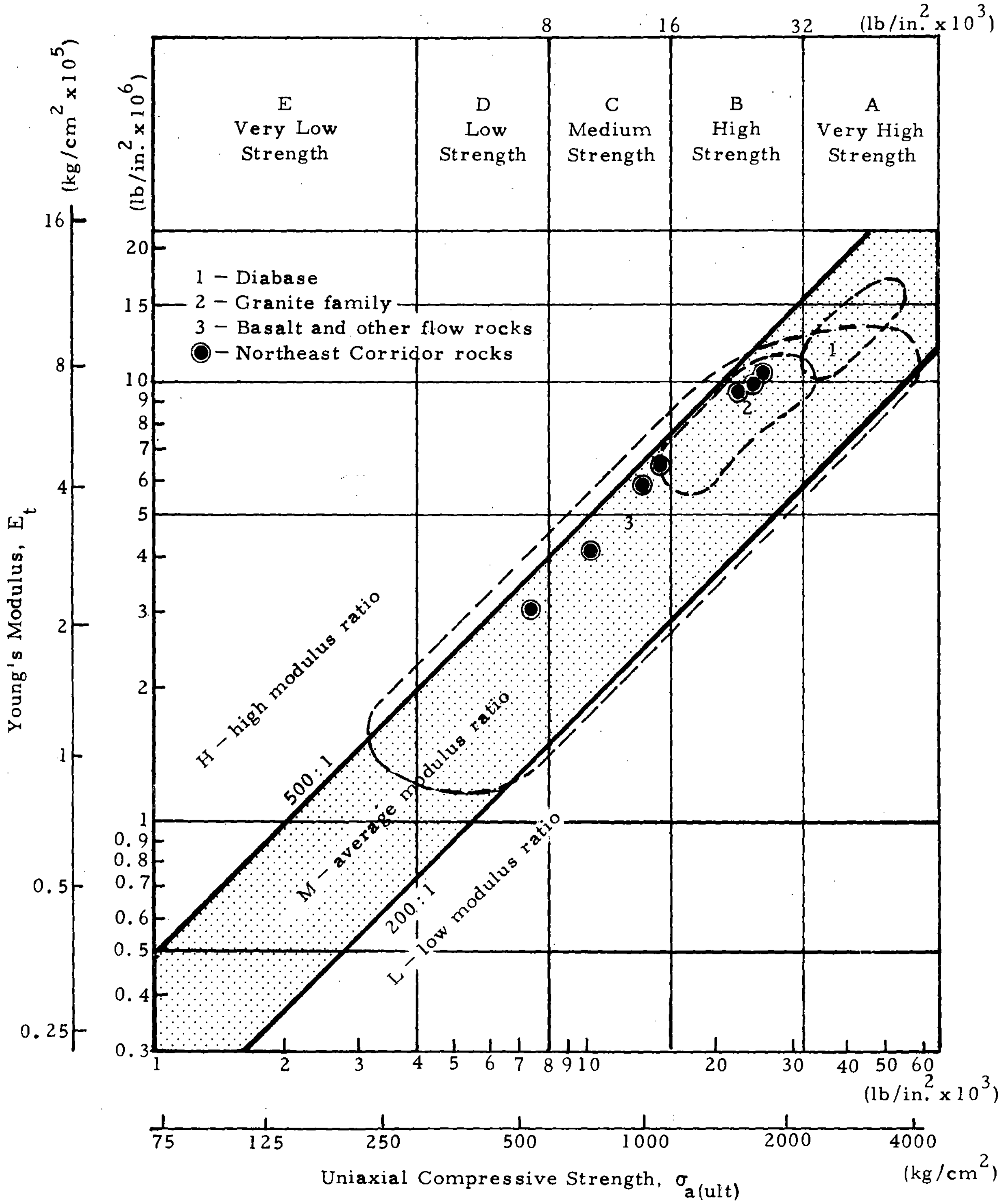


FIGURE 7-11d

COMPRESSIVE STRENGTH, YOUNG'S MODULUS RELATIONSHIP SUMMARY PLOT (176 SPECIMENS) - IGNEOUS ROCKS

After Deere, et al[4]

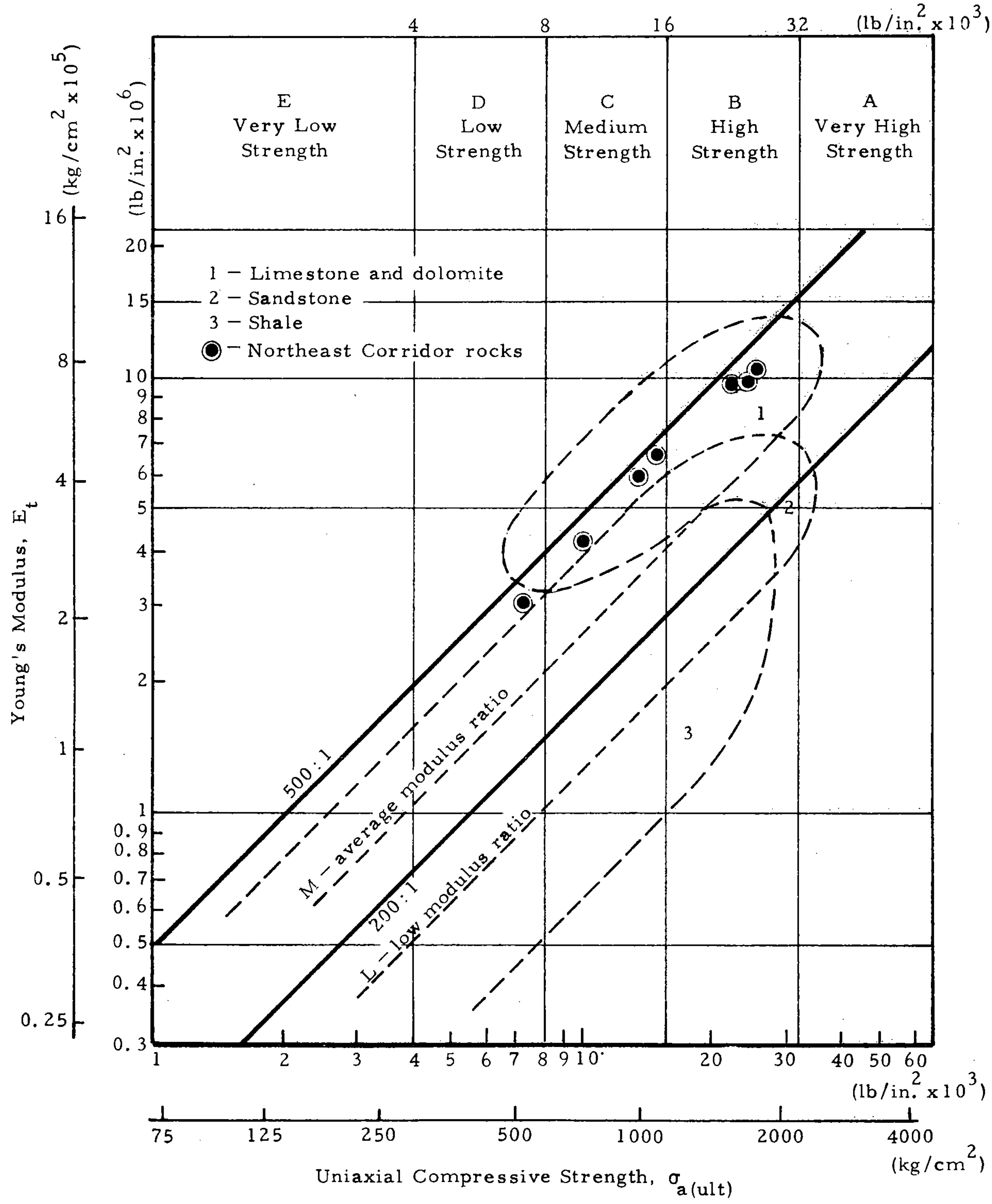


FIGURE 7-11e

COMPRESSIVE STRENGTH, YOUNG'S MODULUS RELATIONSHIP
SUMMARY PLOT - SEDIMENTARY ROCKS
After Deere, et al[4]

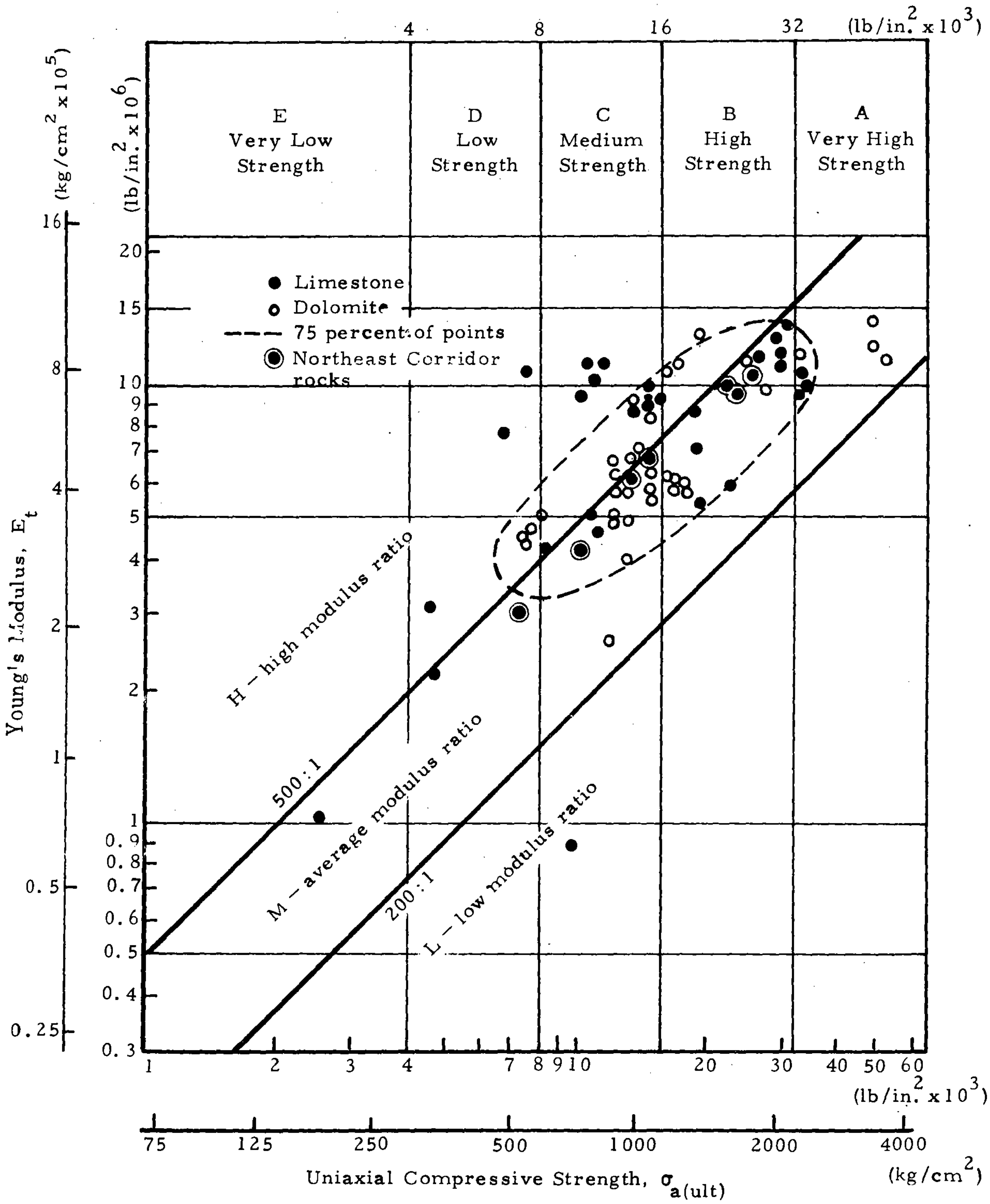


FIGURE 7-11f

COMPRESSIVE STRENGTH, YOUNG'S MODULUS RELATIONSHIP SUMMARY PLOT - LIMESTONE AND DOLOMITE

After Deere, et al[4]

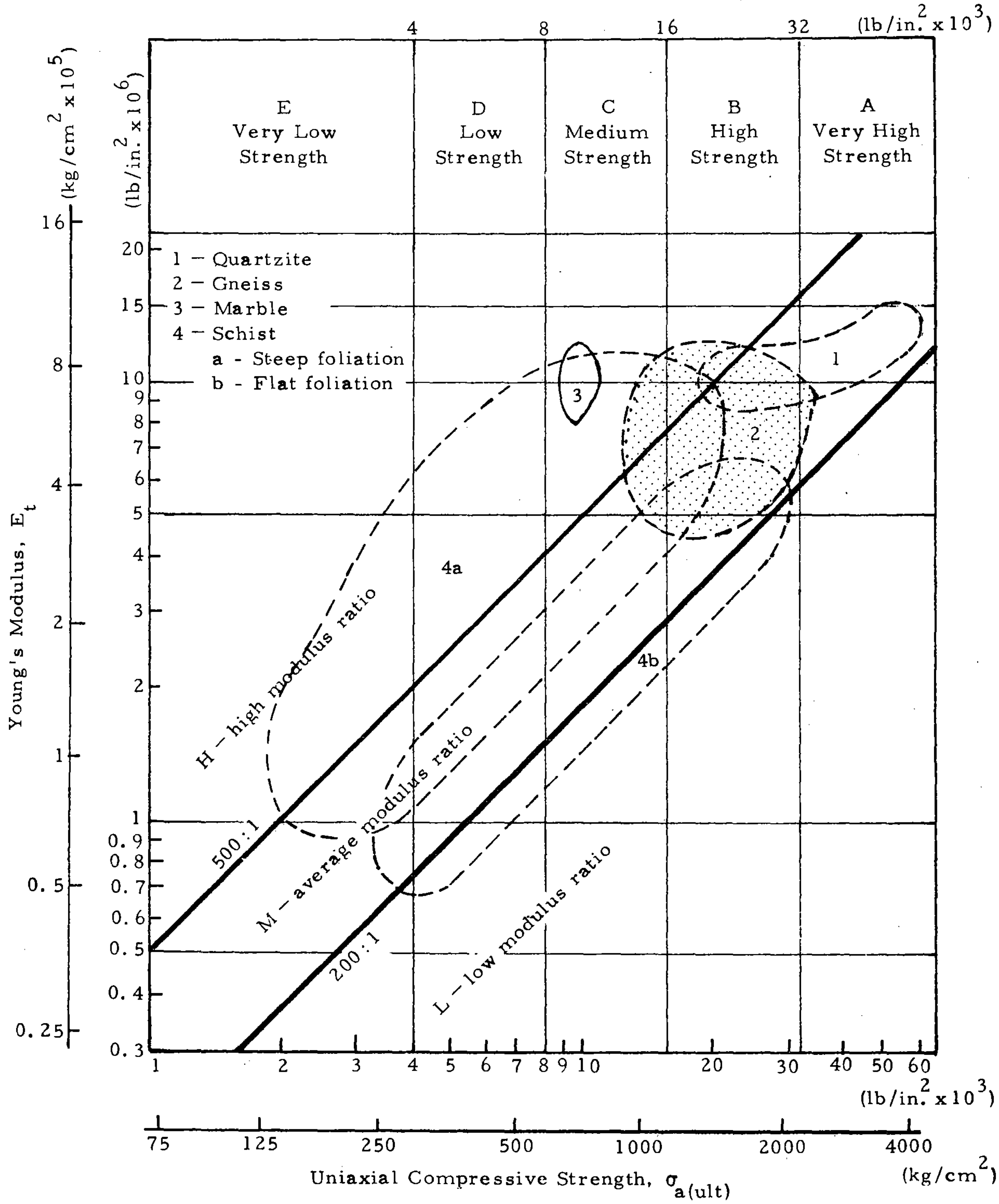


FIGURE 7-11g

COMPRESSIVE STRENGTH, YOUNG'S MODULUS RELATIONSHIP SUMMARY PLOT - METAMORPHIC ROCKS

After Deere, et al[(4)]

Rock Classification, Excavation Method, and Muck Classification

The relationship of engineering properties of rock to actual muck characteristics has not been correlated at present, but there are certain relationships that can be established. Very hard rock tends to break blocky when blasted; and if fine grained, it will have very sharp edges that can slit a conveyor belt for its full length if it happens to become wedged in a certain way at a transfer point or in the structural framework of the conveyor. Also, such sharp abrasive rock causes excessive tire wear on rubber-tired vehicles that can increase tire costs by a factor of 10. Slabby rock can also be bothersome on a conveyor for the same reason, and soft cohesive rock can cause excessive spillage by sticking to the belt and then falling off on the return idlers.

If these same types of rock are broken or excavated by a mechanical boring machine, another set of characteristics are developed. The very hard rock will break into much smaller fragments, and a greater amount of fines will be evident. Medium hard rock will have larger pieces and less fines, unless the cementing material is very soft as in the case of some conglomerates or sandstones. The soft cohesive rock usually must be cut from the face with drag bits; and in many cases, very large chunks are torn loose that cause trouble in handling.

On the other hand, the presence of fines in the muck as found in the shales and cohesive rock, are a considerable advantage when considering transport and hoisting by hydraulic pumping.

Generally, the method of handling the muck is dependent upon the method of mining, as the muck characteristics will vary as shown in the columns under "Blasted Muck" and "Mechanically Excavated Muck" (Figure 7-2). The descriptions shown in Figures 7-1 and 7-2 for the Northeast Corridor are general and do not provide firm conclusions for possible characteristics of the muck based only on the information available. The results of compressive strength tests and Young's modulus of elasticity do not indicate much other than that rocks with high values generally indicate competent, hard, well compressed rock without the presence of excessive amounts of voids or cracks. It is indicated that both sets of values for compressive strength and modulus of elasticity were derived from static tests and the compressive strength classification is for uniaxial compressive strength of intact rock. It was reduced by physical defects and chemical alteration in rock and might differ with respect to bedding, foliation, or direction of principal residual stress. Young's modulus also has been inferred for intact rock reduced by physical defects and chemical alteration. It will also differ with respect to bedding, foliation, or direction of principal residual stress.

The determination of the relative drillability in Figure 7-1 was primarily established from these data which account for roughly 40 percent of the rock to be encountered. Considering the present state of the art, it could be expected that such rock would be too hard to be efficiently bored with mechanical moles. However, the recent excellent performance of a mechanical mole on the River Mountain Tunnel in Nevada and the Azatea Tunnel in New Mexico indicates that only minor improvements are required in bit design to make boring of the hardest rocks economical. Therefore, it has been assumed that it is presently feasible, and the type of muck to be expected for such hard rock has been predicted.

The discrepancies of values between static and sonic measurements* could indicate and help to pinpoint areas of weakness and high fracturing, and thereby give an indication of the muck characteristics to be expected regardless of whether it is excavated by boring or blasting.

Highly fractured rocks will break into much smaller pieces regardless of the method of excavation. Crushed zones will produce an excessive amount of fines, which in the presence of water can be expected to be a very sticky, muddy muck with certain rocks having a high clay content or soft matrix. On the other hand, hard abrasive rocks having a hard matrix would produce a gritty muck even though crushed. Slabby or tabular rocks would probably maintain their general structure, but testing and a considerable amount of research will be required to establish a correlation. It is not proposed that the muck designation number (MDN) presented is correct. It is given as an example of a possible method of designation relating rock characteristics and field and laboratory tests to the muck produced.

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*It is assumed that sonic measurements will be made of the area to provide data for design.

Muck Designation and Transport Systems

The muck produced from conventional blasting is described as blocky, slabby, boulders, pebbles, and cohesive. The sizes are in the range of 18 by 24 inches and, in some cases, are greater for the number 1 classification. The size range progresses through the number 7 classification to muddy, cohesive muck of 1- by 12-inch size. In all cases, the distribution of fines (less than 4 mesh) is present in various amounts in all classifications.

Mechanically excavated muck in the ranges beginning with the number 1 designation progresses from hard, fine, and sometimes foliated material to a muddy, cohesive muck. The size range will vary roughly from 1 by 1 inch for the number 1 designation through 1 by 4 inches in the number 4 designation of slabby material and will gradually drop back again to 1/2 by 1/2 inch in the muddy, cohesive material.

Hydraulically excavated material will follow the range size and description of the mechanically excavated material to a large extent, as it is expected that the water pressure jets used for excavation will have approximately the same effect upon the rock in shattering it into smaller pieces.

Other types of rock shattering or excavation such as thermal, electric shock, and laser are expected to have roughly the same size distribution and somewhat the same characteristics as hydraulically or mechanically excavated material. With high temperature, fusion might take place and sintering or other physical change in the rock could be expected. However, it is expected that the physical change in the rock would be less important than other factors such as high temperature, large heat content, and gas and noxious fume production which could have severe impact on the handling and transport of the material.

Free vehicles, though they possess great flexibility, would not be considered highly desirable when handling muck of designations 1, 2, and 3, especially when conventionally blasted, since the sharp abrasive material could cause cutting and excessive tire wear. On the other hand, for designations 3, 4, and 5, and possibly 6 and 7, if the water content is not too high, rubber-tired vehicles would be satisfactory. If the water content were high, the extreme slipperiness of designations 6 and 7 could be troublesome because of lack of traction and bogging down of the vehicles.

Conventional rail transport can be used throughout all designation ranges but for designations 6 and 7, where highly cohesive wet muck is encountered, hydraulic transport should be given consideration.

Conveyor systems are applicable to handling most of the muck developed by blasting in all seven designations, but consideration would have to be given to coarse crushing rock designations 1 through 5. Mechanically or hydraulically excavated rock would be amenable to conveyor transport for designations 1 through 5, but might give trouble because of spillage caused by sticking to the belt for designations 6 and 7.

Hydraulic transport systems could be developed to handle all rock designations and are especially suited to numbers 1, 2, 6, and 7 from which a considerable amount of fines would be developed, particularly if hydraulically excavated. If precrushing were employed, then all seven designations could be handled regardless of the excavation process.

Pneumatic transport is especially applicable to muck designations 6 and 7 if the material is dry. Material consisting largely of shales, sandstones, and mudstones will contain a large percentage of fines and when broken and dry would handle like a flour or dust. If wet, however, this material would be more adaptable to a hydraulic system.

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CHAPTER 8

GROUND SUPPORT MATERIALS

The type of ground support used in tunnel construction is a function primarily of the ground condition. The integrity of the rock, cohesiveness of the ground material, and hydrostatic pressure affect the load which must be carried by the ground support system. In general, the condition of the ground improves with moderate depth. Less frequent occurrence of fissures, discontinuities, and unconsolidated earth is found; however, the loads requiring support will increase with depth in those cases where less competent rock and difficult conditions exist.

The method of excavation used also influences the type of ground support required since the less damage done to the rock remaining around the tunnel circumference, the more load it can carry and the less support required. The appropriate excavation method is, in turn, determined by the ground conditions. Although a Swiss boring machine using four rotary heads with tungsten carbide bits is reported to be capable of excavating material of greater than 25, 000 pounds per square inch, sustained operation in materials much beyond this range will probably not be practicable within the next several years. Mechanical boring excavators at the present time are also unsuitable for highly abrasive, unconsolidated, sticky, very wet material, or mixed face situations. Mixed face situations can cause severe problems since tunnel excavators are usually designed for a particular type of material and in the present stage of development cannot easily be adapted to work in other materials or in two material types simultaneously. Conventional drill and blast, mechanical claw excavators, or hand methods must be used under these conditions.

The drill and blast technique causes the greatest damage to the surrounding rock and also causes the largest amount of overbreak which requires additional support or liner material to provide the desired finished tunnel diameter. Boring machine excavation reduces overbreak to the minimum.

The drill and blast procedure is normally cyclic, consisting of:

- Drill holes for explosive.
- Load explosive and blast.
- Ventilate.
- Scale loose material from heading advance.

- Remove muck from work zone.
- Install structural support.
- Advance drilling equipment.

It is difficult to envision major increases (order of magnitude) in the rate of advance being achieved by this method; but the possibility must not be ruled out as the cyclic method was predicted to be obsolete 10 years ago, but it is still the most used system. At the advance rates achieved by the drill and blast method, even though more support material is required per unit length of tunnel, the material handling problem is greatly reduced because the quantity rate of material flow is much less than that required for the advance rates achieved (approximately 400 feet per peak day in soft rock) and predicted for mechanical excavators. However, until mechanical excavators are developed which can handle the hardest and most abrasive rock encountered or until there is absolute assurance that no rock will be encountered beyond the capability of the excavator, a means must be provided for transporting to the working face all materials required for drill and blast operations.

Special situations require special excavation and support techniques which require special support materials. Although needed infrequently at depths below 500 feet and in relatively small quantities, these materials cannot be ignored in selecting a material handling system; since when they are needed, a means must be available for getting them to the working zone.

There are five basic methods of ground support which may be used singly or in combination. The first, which is appropriate only for highly competent rock, requires no supplemental supporting materials. The load is supported by the natural arch formed in the rock.

For less competent rock, the formation of this arch is aided by the use of rock bolts which increases the cohesiveness of the rock and distributes the load. The rock bolts often are supplemented by wire mesh or plates spanning between bolts to prevent loose rock from falling.

Shotcrete and gunite are examples of mass materials applied to the surface of the rock to reduce spalling and act in compression to provide structural support and prevent movement of the rock. Chemical materials polymerized in place have also been suggested for this use.

Rib sets are structural steel arches or full circles which may be designed to support most loads so far encountered. The rib set is assembled as close behind the working face as is feasible from two or more components which are fabricated from standard structural steel shapes. Depending on the particular design, one or more types of members may be used. Ribs may be segments of a circle, arch and straight leg, or segments of a horseshoe shape. Wall plates, posts, invert struts, and knee braces are other members which may be used. In addition to the ribs, the complete support system may include lagging between the ribs and auxiliaries such as bracing, tie rods, spreaders, purlins, blocking, and other miscellaneous items. The lagging may be any one or a combination of several types such as wood, steel channel or beams, beams with plates, watertight steel lagging, or pressed steel plates.

Liner segments are structural members of cast iron, steel or concrete, or a combination of these, which combine the load support capability of rib sets with the full surface protection against falling rock afforded by lagging used with rib sets. In some designs, the initial installation of liner segments also provides the final tunnel surface. In other cases, the final lining is applied later in the construction sequence.

Packing is a material used to fill the space between the rock surface and the liner or lagging and ribs. Its purpose is to transfer the rock load uniformly to the structural support system.

In special situations such as unconsolidated ground, excessive water flow, or swelling ground, special materials are required preceding, during, or following excavation to cope with the situation. Some of the materials used for stabilizing the ground or waterproofing are grout, liquid nitrogen for freezing, bituminous cloth, water stops, and "weepers." Special structural components are crush lattice, yielding lagging, spiles, crown bars, and truss panels. Although the need for these special materials is relatively infrequent and the quantities required are relatively small, they should not be overlooked in the selection of a material handling system since when needed there must be a means of transporting the material to the point of use.

The loads imposed on the support system are very difficult or often impossible to predict and may vary over a wide range in a given segment of tunnel. Therefore, more than one method of support may be required to handle the situation most economically. This implies a material handling system capable of transporting the materials for any desired method of support.

Of the basic methods, only the mass materials such as shotcrete offer the possibility for continuous installation. The use of shotcrete in moderately incompetent ground has been quite successful, and the possibility of extending its usefulness into moderately heavy ground by reinforcing it with rebars should be investigated. Installation of liner segments might approach a continuous process by careful development of procedures and equipment, but they would lack the flexibility to adapt to the variation in load requirements that can be obtained by application of various thicknesses and strengths of shotcrete. Since there is some doubt that shotcrete will be adequate under heavy squeezing ground or other unusual situations, ribs or liner segments may always be needed in these cases.

Nearly all tunnels constructed for permanent use are lined with concrete to the final design dimensions. Most designers have not considered this secondary lining to be part of the ground support system, thus permitting its installation after all excavation has been completed to avoid interference with the excavating and earth support operations. However, as more attention is given to reducing the cost of tunnels and improving the design of the earth support systems, there may be a strong incentive to install the secondary lining as close behind the excavation as possible. Installing the secondary lining simultaneously with excavation has the obvious disadvantage of reducing the already limited space available for transport of materials and equipment to and from the working zone.

RIB SETS

There are two major sets of conditions which determine the need for rib support. These are: (1) the tendency for cohesionless or plastic material to invade the tunnel; and (2) the tendency of a mass of rock to drop out of the roof or back. For conventional excavation, the rock overbreak above the required roof line seldom extends beyond one-half the width of the tunnel; for mole excavation it is much less. If structural supports are advanced as close to the heading as possible and immediately after blasting, less movement of rock in the overbreak zone will occur and less load will be imposed on the supports, thus requiring less support material.

Rib supports can be made from wood or steel. However, the use of steel supports has almost completely replaced the use of wood for commercial tunnels other than mining due to the smaller excavation diameter required for a given finished tunnel size and the greater ease and speed of installation, both resulting in less overall cost per foot of tunnel advance. In extremely poor ground where only full-circle ribs provide adequate support, steel and reinforced concrete are the only materials found satisfactory. With present-day commercial capacity for bending beams of any size up to 16-inch wide flange beams and press capacity for larger sections, the ability exists to provide any size and shape of steel support desired.

The use of steel rib sets, most frequently required on 36 to 48-inch centers, usually requires a secondary concrete lining to protect the steel and exposed rock if long term use is expected.

A rib set may consist of several structural steel members such as continuous ribs, arch ribs, wall plates (flat or double beam), posts, invert struts, or knee braces.

Configuration

Steel rib supports are used in several configurations depending on the method of excavation, rock condition, and tunnel size and shape. The most common configurations are shown in Figure 8-1, and the conditions to which they are most suited are indicated in Table 8-1.

The continuous rib configuration can be used with straight sides, or curved sides to form a horseshoe. Continuous ribs can be used with or without the invert strut, depending on the side pressure exerted by the tunnel wall. Figure 8-2 is a composite showing continuous rib support on one side and rib, wall plate, and post support on the other side. It also shows several other elements of the primary support system (blocking, lagging, and foot blocks) and the secondary support and liner concrete. The liner in this case forms a horseshoe tunnel, but it could be placed to form a circular tunnel.

Recently, a new configuration was developed at the Nevada Test Site for the U.S. Atomic Energy Commission. The legs of the ribs are canted outward 1 inch per foot from the vertical. This provides greater support against mild side pressures.

When a horseshoe tunnel is supported and finished to form a circular cross section, more excavation, more steel, and more concrete are required than if the excavation is made circular as shown in Figure 8-3. The full circular support provides greater strength per unit weight of steel than any other configuration. Where ground pressures are relatively light, horseshoe or circular liners can be formed without steel supports.

The structural members from which rib sets are made can be H-beams, I-beams, stanchions, light beams, wide-flange beams, or rails (sometimes used for invert struts). Typical dimensions and weights per foot of length are shown in Table 8-2.

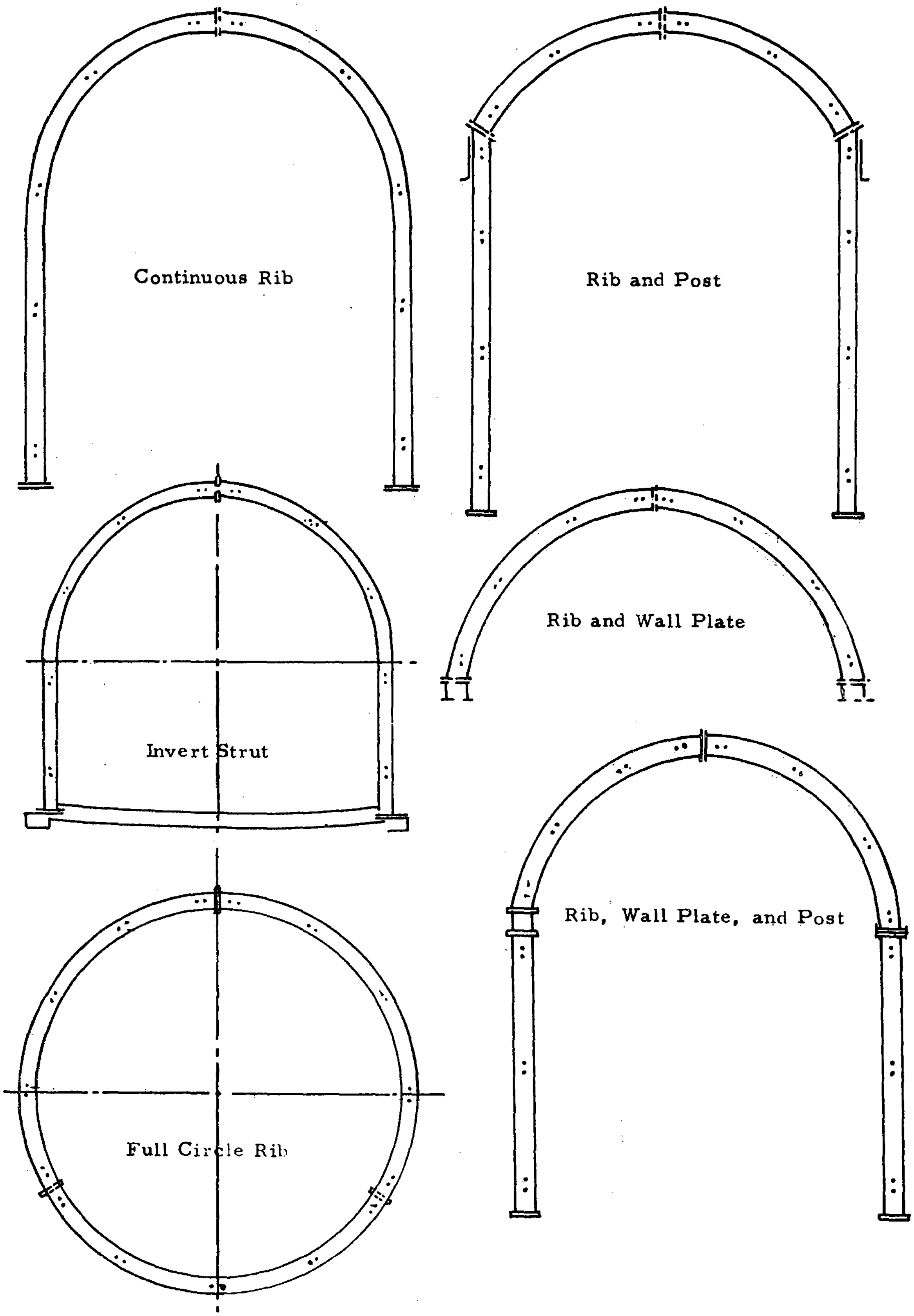


FIGURE 8-1

STEEL RIB SUPPORTS
After Proctor and White[1]

TABLE 8-1

RIB SETS[1]

(Ground Condition Requirements)

Rib Type	Number of Pieces	Usual Excavation Methods	Ground Conditions
Continuous Rib	Usually 2; sometimes 3 or 4	Full face, side drift, multiple drift	Little or no side pressure.
Canted Steel Set	2	Full face	Mild side pressure.
Yieldable Arch Sets	2	Full face, heading and bench	Considerable side or back pressure; squeezing, swelling, or crushed rock; earth tunnel conditions.
Invert Strut or Arch	Usually 3	Full face	Mild side pressure; heaving bottom.
Concrete Floor and Curb	Poured in place	Full face	Swelling bottom; considerable side or back pressure; squeezing, swelling, or crushed rock; earth tunnel conditions.
Full Circle Rib	3 to 6	Full face, heading and bench	Considerable side or back pressure; squeezing, swelling, or crushed rock; earth tunnel conditions.
Rib and Post	4	Full face, multiple drift, side drift, heading and bench, top heading	Roof arch angled in respect to side wall; in tunnel sizes too large for continuous rib to be handled; early support required for roof in drift.
Rib and Wall Plate	4 to 6	Heading and bench, top heading, full face	Circular or high sides where only light roof support needed.
Rib, Wall Plate, and Post	6 to 8	Heading and bench, top heading, side drift, full face	Where post and rib spacing differ; quick support needed for roof; large tunnels with bad rock; favorable rock where support not needed tight to face; roof arch angled in respect to side wall.

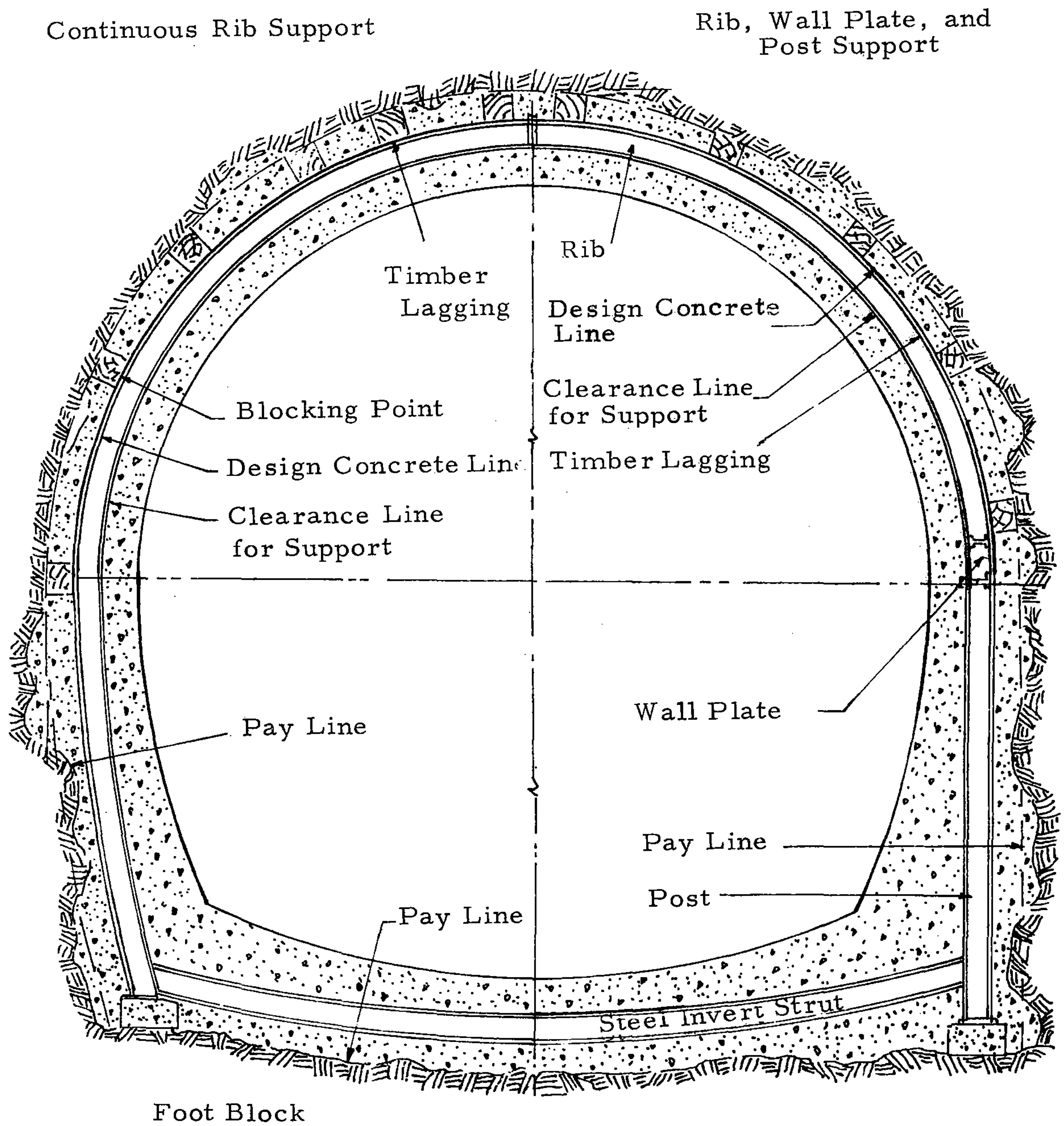


FIGURE 8-2

COMPOSITE OF CONTINUOUS RIB SUPPORT AND CONTINUOUS WALL PLATE

After Mayo(2)

TABLE 8-2

WEIGHT AND SIZE OF TUNNEL RIB MEMBERS

Beam	
Nominal Depth, Flange Width and Type (Inches)	Weight Per Foot (Pounds)
4 I	7.7
4 x 4 H	18.0
5 I	10.0
5 x 5 Stanchion	16.0
5 x 5 H	18.9
6 I	12.5
6 I	17.25
6 x 4 Light Beam	12.0
6 x 4 Light Beam	16.0
6 x 6 Stanchion	15.5
6 x 6 H	20.0
6 x 6 H	25.0
7 I	15.3
8 I	18.4
8 I	23.0
8 x 5 Light Beam	15.0
8 x 8 H	34.3
8 x 5-1/4 W.F.	17.0
8 x 5-1/4 W.F.	20.0
8 x 6-1/2 W.F.	24.0
8 x 6-1/2 W.F.	28.0
8 x 8 W.F.	31.0
8 x 8 W.F.	35.0
8 x 8 W.F.	40.0
8 x 8 W.F.	48.0
8 x 8 W.F.	58.0
8 x 8 W.F.	67.0
10 I	25.4
10 I	35.0
10 x 5-3/4 W.F.	21.0
10 x 5-3/4 W.F.	25.0
10 x 8 W.F.	33.0
10 x 8 W.F.	39.0
10 x 8 W.F.	45.0
10 x 10 W.F.	49.0
10 x 10 W.F.	54.0
10 x 10 W.F.	66.0
12 x 8 W.F.	45.0
12 x 10 W.F.	53.0
12 x 12 W.F.	65.0

Ribs

Terzaghi[1] has developed formulas for estimating the rock load expected to develop for conventionally excavated tunnels. These loads determine the structural member size and spacing required. Since his formulas were developed prior to the development of boring machines, they do not give values for bored tunnels. The Harza study[3] used the assumptions in Table 8-3 to calculate reduced rock loads for bored tunnels under Terzaghi conditions 1 through 8.

TABLE 8-3

ROCK LOAD REDUCTION FACTORS FOR BORED TUNNELS[3]

Terzaghi Condition	Reduction of Rock Load		
	8-Foot Tunnel		40-Foot Tunnel
1	No supports in either case		
2 and 3	90%	to	75%
4 and 5	75%	to	50%
6, 7, and 8	No reductions		

Proctor and White[1] and Hair[4] have made estimates and observations for the spacing and type of rib support required under various conditions. These are summarized in Table 8-4.

Harza[3] has calculated the pounds per linear tunnel foot of steel support ribs required for various rock classes at various depths for both conventional and bored excavation methods. The quantities are shown in Table 8-5, and the sizes of the structural members required are given in Table 8-6.

Wall Plates

Wall plates may be either flat or double beam as shown in Figure 8-1. Flat wall plates are wide-flange beams or I-beams with the web layed horizontal. The ribs and posts are placed between the flanges. This configuration provides little vertical strength and requires a post under each rib. The double-beam wall plate provides greater vertical strength allowing irregular spacing of posts.

TABLE 8-4

CUSTOMARY RIB SPACING

Rock Condition	Rib Spacing (On Centers)	Remarks
Hard and intact		Steel support usually not required. Light lining required only if spalling or popping occur.
Massive, moderately jointed stratified or schistose; wet or dry	6 feet	None required in some sections.
Moderately to very blocky and seamy; wet or dry.	6 to 4 feet	Little or no side pressure.
Dry unconsolidated or completely crushed	2 feet	Considerable side pressure; circular ribs or braced bottom.
Wet unconsolidated, crushed, or squeezing ground	2 feet or less	For heavy side pressures, invert struts required; circular ribs recommended.
Swelling rock	2 feet or less	Circular ribs required.

TABLE 8-5

STEEL SUPPORT IN TUNNELS[3]
(Pounds Per Linear Foot)

Excavation Diameter (feet)	Rock Class	Drill and Blast				Bored			
		Depth (feet)				Depth (feet)			
		100	500	1000	2000 to 3500	100	500	1000	2000 to 3500
8	I	14	8	5	4	3	1.5	1	1
	II	25	21	14	10	6	7.5	5.5	4.5
	III	30	25	21	16	7.5	6	4.5	2.5
	IV	24	20	15	12	6.5	5	3.5	2.5
	V	35	28	27	33	9	7.5	10.5	23.5
	VI	45	44	43	48	29	37	36	42
	VII	63	63	63	76	50	50	50	69
20	I	86	48	34	25	25	13	9	7
	II	162	150	108	81	52	68	53	45
	III	192	158	138	99	65	49	41	23
	IV	155	130	92	74	54	44	28	20
	V	225	177	199	330	82	61	98	242
	VI	402	446	433	511	283	361	356	429
	VII	623	623	623	833	495	495	495	
30	I	265	146	102	74	91	46	32	26
	II	475	444	315	242	187	235	185	159
	III	577	464	396	272	232	180	145	85
	IV	478	401	281	233	193	155	100	73
	V	680	523	600	1052	290	218	343	822
	VI	1264	1419	1375	1640	933	1192	1173	1425
	VII	2020	2020	2020	2730	1635	1635	1635	2345
40	I	547	299	208	154	241	120	82	68
	II	1035	992	710	549	500	589	445	373
	III	1250	1010	865	600	625	479	386	220
	IV	1015	847	548	475	517	417	264	194
	V	1470	1135	1340	2440	778	579	859	2002
	VI	2890	3305	3210	3840	1776	2363	2310	3451
	VII	4670	4670	4670	6370	4020	4020	4020	5720

TABLE 8-6

STEEL SUPPORT WEB DEPTHS[3]

Excavated Diameter (Feet)	Rock Class	
	I through V (Inches)	VI and VII (Inches)
8	4	5
20	6	8
30	8	8
40	8	10

The wall plate is sometimes supported on pins set in holes drilled in the side wall. It is blocked to line and grade, and then the roof ribs are set in place and blocked. The wall plate is supported vertically and horizontally by posts and blocks installed at favorable points in the overbreak at a later time.

Typical wall plates are 6-, 8-, or 10-inch H-beams or I-beams from 8 to 16 feet long. Pins are usually round dowels 1 inch in diameter and about 4 feet long.

Posts

Posts are usually H-beams, I-beams, or wide-flange beams. Typical sizes are 8 by 6.5 or 8 by 8. In some cases, larger members are used as posts; for example, the very severe squeezing ground condition of parts of the Moffat tunnel required 20-inch I-beams as posts. A full circle, 10-inch wide flange rib would have provided equal strength. An 18-inch thick skintight timber lining had been found unsatisfactory under the same conditions. Typical posts would be from 5 to 20 feet long.

Invert Struts

Invert struts are typically I-beams or H-beams somewhat smaller in size than the posts; sometimes 85-pound rail is used. The length of the invert strut would be of the same order as the tunnel diameter.

Knee Braces

Knee braces can be any convenient structural member. They are usually from 2 to 4 feet long.

LAGGING

"Lagging" is the term applied to those elements of the tunnel support system which span between the rock supporting ribs or posts. It serves one or more of the following functions.

- Provides protection from falling rock.
- Transfers loads to the rib sets.
- Provides surface for blocking in case it is not convenient to block against the rib.
- Provides surface against which to place back-packing.
- Serves as outside form if concrete lining is not to be poured against the rock.
- Diverts water to prevent leaching of concrete.

There are many alternate types of lagging in common use. Several types are shown in Figure 8-4. The lagging composing several of these types can be placed either fairly wide apart as "skeleton" or "open" lagging or continuous to form a "tight" lagging.

By far the greatest footage is driven with skeleton lagging to allow flow of concrete into the space behind the lagging. Spacing is closest at the crown and increases rapidly to the spring line. On the sides, only occasional lagging is used.

Lagging can be either wood or steel, but steel is more popular for permanent tunnels since good practice requires that all wood lagging and blocking not actually under load be removed prior to concreting.

Wood lagging consists of hardwood planks 2 to 4 inches thick by 6, 8, 10, or 12 inches wide. These are cut to length slightly less than the rib spacing (usually 2 to 5 feet) and are either placed on the outside flange or, most commonly, placed in the web of the steel set either spaced or tight to form a continuous skin, depending on the quality of the rock.

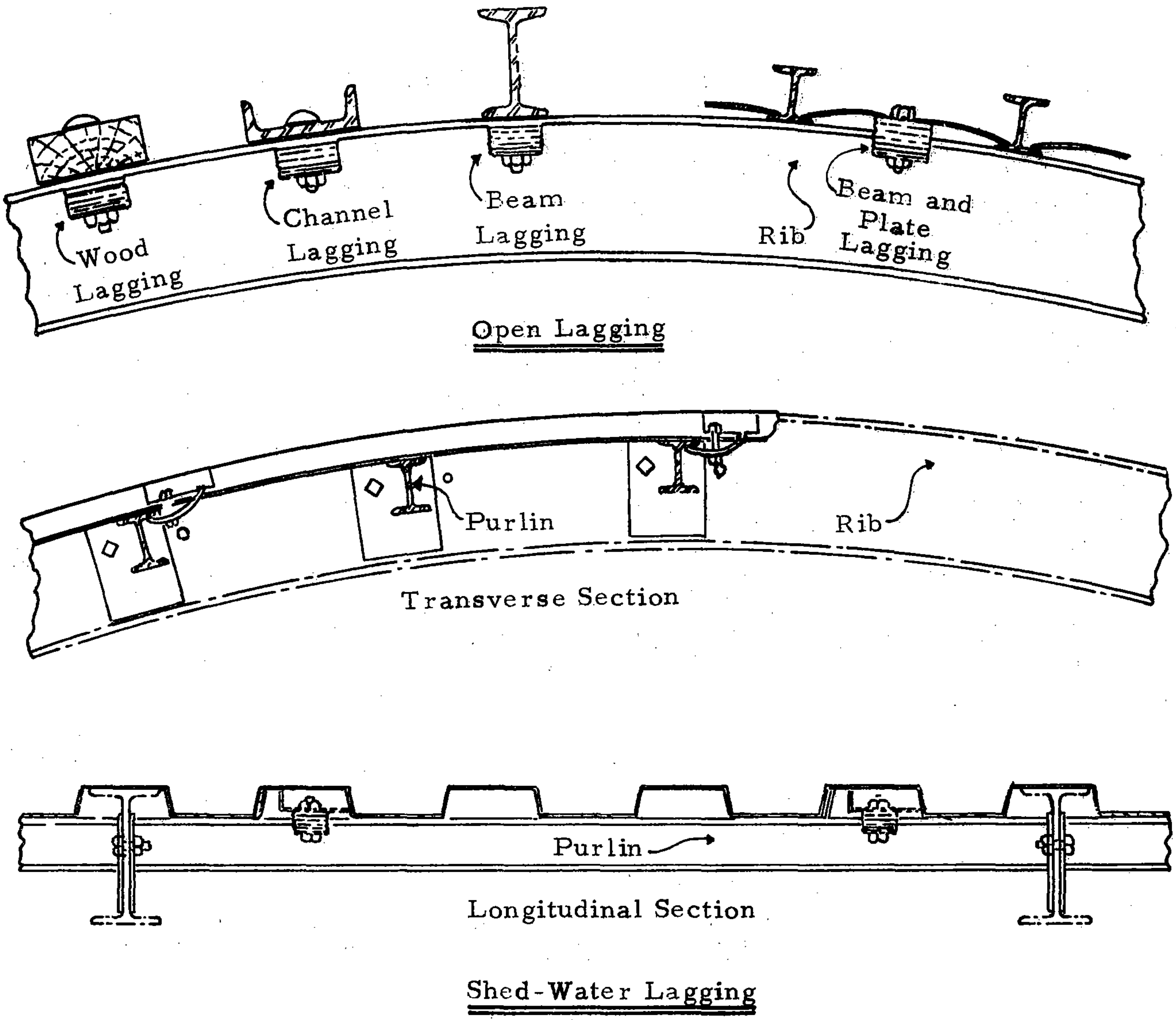


FIGURE 8-4

TYPES OF LAGGING
After Proctor and White[1]

Channel lagging consists of rolled or pressed steel channels 4, 5, or 6 inches wide (the most commonly used is the 6-inch wide at 8.2 pounds per foot) placed flat on the ribs with flanges outward as shown. This is the steel equivalent of wood lagging and may be continuous or spaced. Seventy percent coverage of the crown or continuous over 60 degrees of the crown is typical.

Beam lagging can be any size but usually consists of 4- or 5-inch deep, rolled steel H-beams attached to either flange of the rib at spacing suitable to the rock condition.

Beam and plate lagging has slightly curved plates clamped to the flange of the ribs to hold the plates and supporting 3-, 4-, or 5-inch I-beams in place. The plates can be any size desired but small enough to retain stiffness and ease of handling.

Shed-water or water bar lagging makes use of purlins to support special lightweight plates over the outer flanges of the rib and the purlins so as to provide a water diverting skin of steel. Typical purlins are 3- or 4-inch I-beams or 4- or 5-inch channels 3 to 5 feet long.

The plates for purlin-plate lagging are corrugated sheet metal usually 18 to 30 inches wide and up to 10 feet long. The gauge can be any thickness to suit the rock load. The plates for shed-water lagging are fabricated from light gauge (e.g., 18 gauge) sheet metal to the special shape shown in Figure 8-4. They are provided in any length up to 10 feet and are usually about 30 inches wide by 3 inches thick.

Liner plate lagging consists of pressed steel plates attached between the webs of the ribs to make a tight lagging which is ideal in many rock tunnels where the overbreak is to be filled with dry pack, gravel, or concrete and is used extensively in earth tunnels as well. Methods of attachment of liner plates are shown in Figure 8-5. Lateral bracing is not required in the plated sections of the support system. In some cases liner plates have been used without ribs by bolting them together to form a liner plate arch.

Typical liner plates are 16 or 24 inches wide and 38 or 48 inches long. In special cases, liner plates 96 inches long have been used. Half-plates 19 or 24 inches long are also available. The plate thickness or gauge varies from 1/8 inch to 3/8 inch, and the minimum flange heights vary from 2 to 2.5 inches. Depending on the gauge and flange height, the weight per plate varies from 28 to 82 pounds for 16- by 38-inch plates and 50 to 148 pounds for 24- by 48-inch plates. The bolts used range up to 1/2 pound each with seven required per plate.

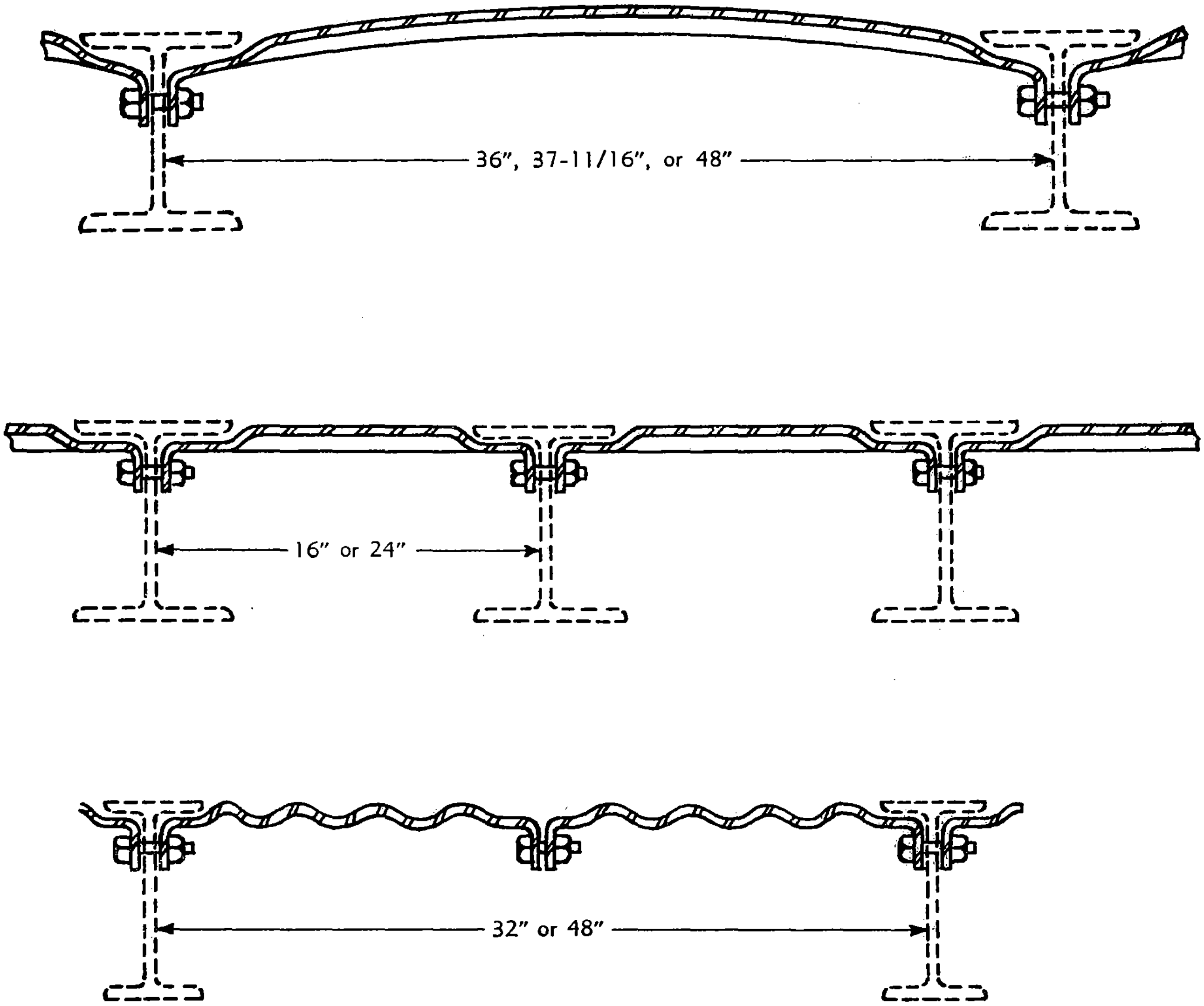


FIGURE 8-5

TYPICAL LINER PLATE

After Proctor and White[1]

In a study by Harza[3] the quantities of wood blocking and lagging were estimated per linear foot of tunnel for various depths and rock classes when excavated by conventional means and also when excavated by boring. Due to the lack of sufficient data for bored tunnels, the estimate of these quantities was based on the observation that the quantities of blocking and lagging are approximately proportioned to the amount of support steel required. The results of this study are shown in Table 8-7.

AUXILIARIES

Bracing

Lateral bracing or spacers between ribs or posts is provided by wood collar braces (girts) and steel tie rods, or sometimes by slightly heavier tie rods used in compression. Spreaders made from angles, channels, or I-beams are another common form of bracing. If lagging is firmly attached to the webs, no additional bracing is required. The purpose of these braces is to prevent displacement of the ribs or posts by falling rock and to increase the resistance to buckling, particularly during blasting. Generally, all wooden collar braces are removed at some distance back from the face and reused ahead before concreting. A typical arrangement of collar braces and tie rods is shown in Figure 8-6.

The collar brace is usually a piece of timber 3 by 4 inches, 4 by 6 inches, 6 by 6 inches, or any other convenient size varying in length to suit the spacing between the rib webs, which is normally between 2 and 5 feet. Spacing of the bracing on the circumference of the tunnel is such that a brace will be near the end of each member of the rib set with intermediate braces not over 5 feet apart.

Tie rods for use with collar braces are available in 3/4-inch or 5/8-inch diameter. If they are to be used alone, 1-inch or 7/8-inch diameter is normally used to reduce the tendency to bend under compression. They can be furnished in random "mill" lengths from 15 to 25 feet to be cut to length (rib spacing plus 3 inches) and threaded in the field. This operation can be performed aboveground and bundles of tie rods transported to the point of installation.

Spreaders and Purlins

Spreaders and purlins are both structural steel members made of angles, channels, or I-beams installed between the webs of the ribs, the only difference being in the function performed.

TABLE 8-7

BLOCKING AND LAGGING IN TUNNELS(3)
(Board Feet Per Linear Foot of Tunnel)

Excavation Diameter (feet)	Rock Class	Drill and Blast				Bored			
		Depth (feet)				Depth (feet)			
		100	500	1000	2000 to 3500	100	500	1000	2000 to 3500
8	I	30	20.5	14.5	9	6.5	4.0	3.0	2.0
	II	31.5	32.5	26	20	7.5	11.5	10	9
	III	33	31.5	30.5	29.5	8	7.5	6.5	4.5
	IV	32	31.5	30	30	8.5	8	7	6
	V	33.5	31.5	33	35.5	8.5	8.5	13	25
	VI	47.5	50	49.5	47	31	42	41	41
	VII	60	60	60	60	47.5	47.5	47.5	54.5
20	I	57	38	27.5	16.5	17	10.5	7.5	4.5
	II	62	64	50.5	39.5	20	29	25	22
	III	67	62	59.5	54.5	23	19	18	13
	IV	64.5	62	57	57	22	21	17	15
	V	69	62	66	73	25	21	33	54
	VI	109	115	113	106	77	93	93	89
	VII	148	148	148	148	118	118	118	125
30	I	80	53	38	22.5	27	17	12	8
	II	87	89	71	56	34	47	42	37
	III	95	87	82	76	38	34	30	24
	IV	91	87	80	80	37	34	28	25
	V	99	87	94	104	42	36	54	81
	VI	161	170	166	156	119	143	142	136
	VII	217	217	217	217	176	176	176	186
40	I	98	65	46	28	43	26	17	12
	II	109	112	88	70	53	66	55	48
	III	120	109	104	93	60	52	46	34
	IV	114	110	99	99	58	54	48	41
	V	125	109	118	132	66	54	76	108
	VI	210	222	216	202	129	158	156	182
	VII	289	289	289	289	249	249	249	260

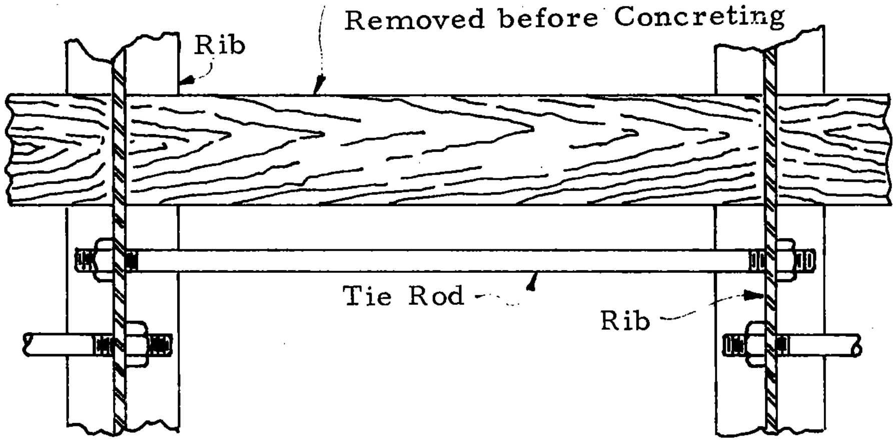


FIGURE 8-6

COLLAR BRACES AND TIE RODS
After Proctor and White(1)

Spreaders, used to space the ribs and give lateral support, are permanently bolted to the ribs with clip angles or plates welded on each end and concreted in. They are usually spaced less than 5 feet apart but may be wider spread, and they are from one-half to three-fourths the size of the ribs. Typical spreaders might be 5-inch I-beams 3 feet long spaced 4 feet apart.

Purlins are installed between the ribs to support light steel plates when this form of continuous skin lagging is desired. They are usually 3- or 4-inch I-beams or may be 4- or 5-inch channels. The length is determined by the rib spacing, 3 to 5 feet being typical.

Blocking

Blocking, which is required wherever steel rib supports are installed, is wedged tightly between the supports and the exposed rock surface at convenient points to transmit the rock load to the supports before appreciable movement of the ground takes place. Irregular spacing of the wood blocks is inherent in tunnel construction to take advantage of the more favorable spots in the overbreak. The spacing would be expected to be more uniform for mechanically excavated tunnels. Block spacing varies from nearly continuous in very poor rock to a maximum dependent on the width of the tunnel as given in Table 8-8.

Blocking is used at the rib footing and at wall plates. Blocking pieces vary from small wedges to blocks approximately 6 by 8 by 24 inches. Occasionally, 4-foot lengths of 4- by 4-inch pieces are used. Precast concrete foot-blocks (12- by 18- by 24-inch or 9- by 12- by 18-inch) are sometimes used.

Cribbing is used where a large opening exists between the supports and the rock or where an extremely large loose slab or boulder has to be supported. It is done by lacing timber together in a "log-cabin" configuration under the rock requiring support.

Where the support required is not as great, a stull and headboard can be used. This consists of a short post braced against the tunnel set with a short piece of lagging placed between it and the rock to effect support over a larger area.

Foot-blocks are also used under posts in areas where the bottom of the tunnel is soft and there is a tendency for the posts to sink.

TABLE 8-8

BLOCKING

Tunnel Width, Feet (To Design Concrete Line)	Blocking Point Spacing, Inches (Maximum)
8	34
10	36
12	38
14	40
16	42
18	44
20	46
22	48
24	50
26	52
28	54
30	56
32	58
34	60
36	62
38	64
40	66

LINING

Tunnel lining is used in conjunction with or in lieu of rib sets. When used with rib sets, the lining may be applied over tight lagging which has been back-packed or over rib sets with open lagging or no lagging. In either case, the lining material is concrete placed by pumping or as shotcrete.

A rough rule of thumb for unreinforced concrete secondary liners is 1 inch of liner thickness for each foot of tunnel diameter. If the drill and blast method of excavation is used, approximately 6 inches (on the average) will need to be added to fill the space created by overbreak.

There is considerable disagreement regarding the design of concrete liners. Some engineers feel concrete lining should be reinforced while others prefer to eliminate reinforcing to save time and reduce cost. Some designers use the concrete lining only to provide long-term protection for the primary supports and rock faces; others feel that the support provided by rib sets should not be considered in the design of the lining, thus requiring a much thicker secondary lining. Liners designed against full hydrostatic pressure present very special problems and will not be discussed in this report.

In the Harza study,[3] the criteria shown in Table 8-9 were used for design of tunnel linings. Application of these criteria produced the nominal concrete lining thicknesses and quantities, allowing for 15 percent overbreak for escavation by conventional methods as shown in Tables 8-10 and 8-11.

Another type of concrete liner which is used in lieu of steel rib primary support, and which may eliminate the need for secondary lining in some cases, is made from precast concrete segments. Several variations of this type of lining are shown in Figures 8-7, 8-8, 8-9, and 8-10.

TABLE 8-9

CRITERIA FOR TUNNEL LINING[3]

Rock Class	Lining Thickness	
	Thickness Per Foot Finished Diameter (Inches)	Minimum Thickness (Inches cover over inside face of steel support)
I	0.5	8
II thru V	0.75	8
VI	1.0	8
VII	1.5	8

TABLE 8-10

TUNNEL LINING THICKNESSES(3)

(Inches)

Finished Diameter	Rock Class I	Rock Classes II-V	Rock Class VI	Rock Class VII
8 ft	12	12	13	13
12 ft	12	12	13	18
18 ft	14	14	18	27
24 ft	15	18	24	36
32 ft	16	24	32	48

The spiral lining is made from solid precast concrete segments which are 30 inches wide and the length of 1/4 of the circumference of the tunnel. For a 20-foot diameter tunnel with a 14-inch thick liner, this gives segments about 16.5 feet long, weighing 3.3 tons each. The rings are tied together by tie rods spaced about 4 feet apart. To make a completely watertight liner, a bitumastic sealant is used in the spiraling joints, the inside surface is covered with a waterproofing fabric, and a secondary concrete lining is installed.

O'Rourke concrete blocks interlock to provide 1/4-inch joints for grouting. Secondary concrete lining of 12 to 15 inches is often used. Each block is approximately 14 inches thick, 3 feet wide, and 7 feet long.

The knuckle-jointed concrete segment is a variation of the O'Rourke block. It is approximately 6 inches thick, 2 feet wide, and 3.5 feet long. No grout is needed as wedges are jacked in the top to expand the ring.

Bolted concrete segments are precast, reinforced block about 2 feet wide and 6.5 feet long. The flange is about 6 inches deep and the skin 2.5 inches thick. Bolted concrete lining costs only about 70 percent of standard cast iron or steel lining.

The precast segments are hauled on flat cars and roller conveyors to the heading where they are positioned by hydraulic erector arms, ring mounted around the muck conveyor system.

Similar liner segments are made from cast iron or fabricated steel as illustrated in Figures 8-11, 8-12, and 8-13.

TABLE 8-11

CONCRETE VOLUMES IN TUNNEL LININGS(3)
(Cubic Yards per Linear Foot of Tunnel)

Finished Diameter (feet)	Excavation Method							
	Rock Class I		Rock Class II-V		Rock Class VI		Rock Class VII	
	Bored	Conventional Cyclic	Bored	Conventional Cyclic	Bored	Conventional Cyclic	Bored	Conventional Cyclic
8	1.1	1.5	1.1	1.5	1.1	1.6	1.1	1.6
12	1.5	2.4	1.5	2.4	1.6	2.5	2.4	3.3
18	2.6	4.4	2.6	4.4	3.4	5.3	5.3	7.5
24	3.7	6.8	4.5	7.6	6.1	9.5	9.5	13.4
32	5.2	10.4	7.9	13.6	10.7	16.8	16.8	23.8

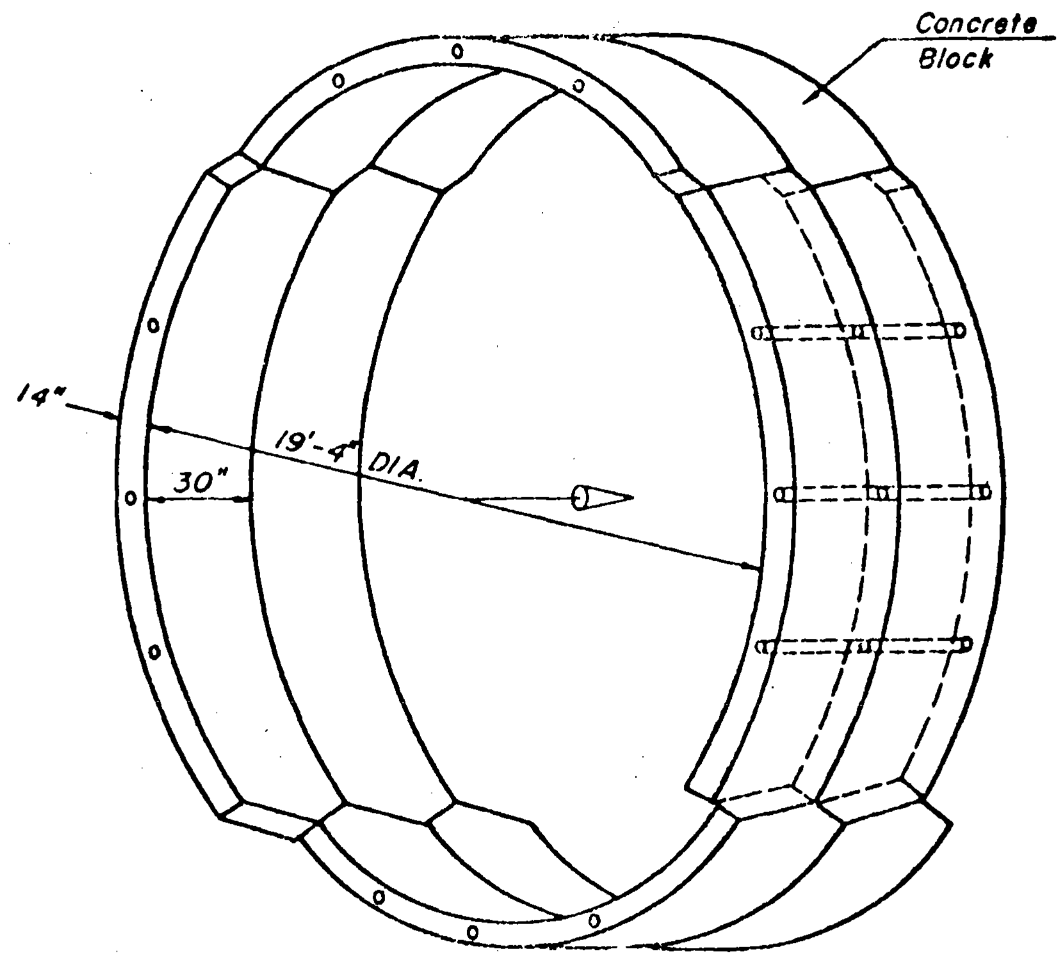


FIGURE 8-7

SPIRAL LINING
After Mayo(2)

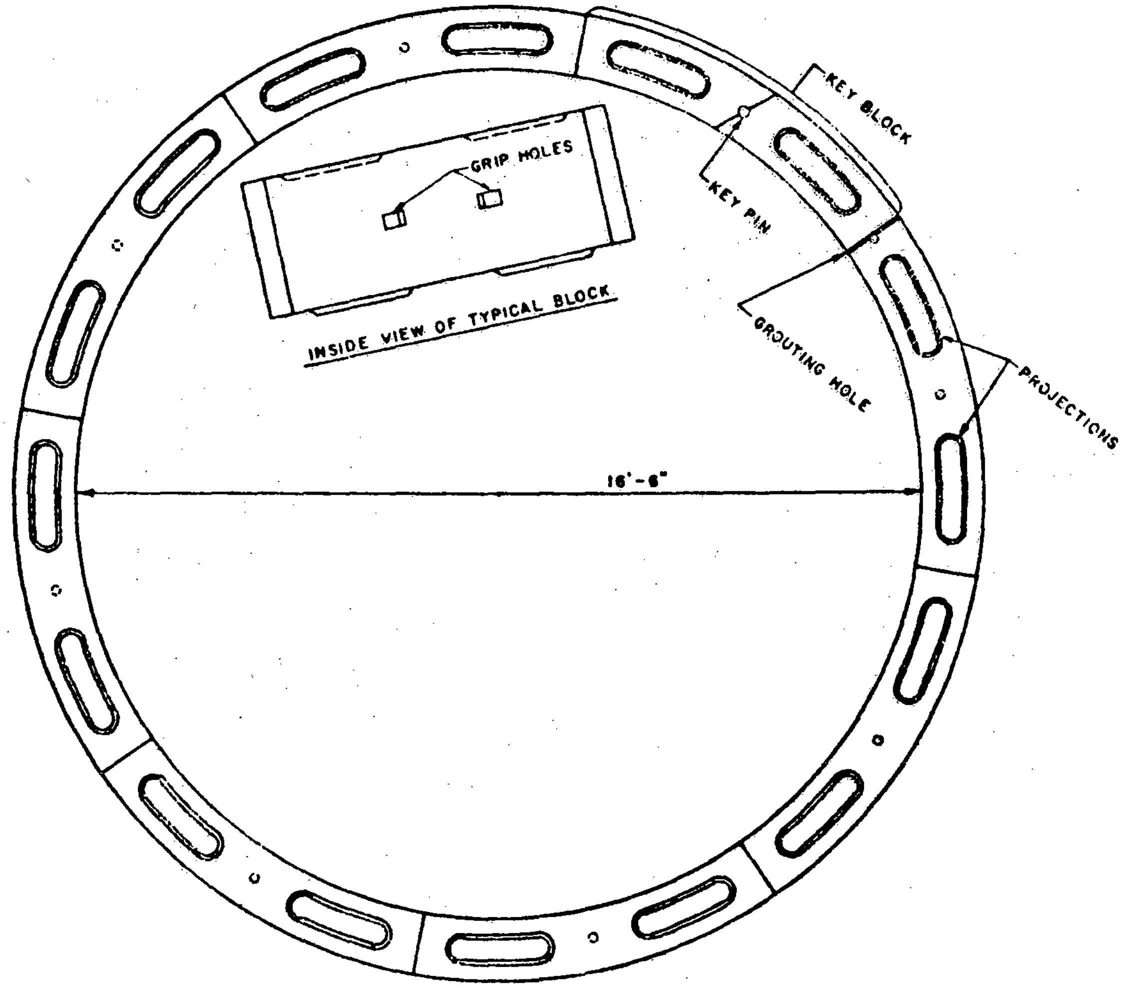


FIGURE 8-8

O'ROURKE CONCRETE BLOCKS
After Mayo[2]

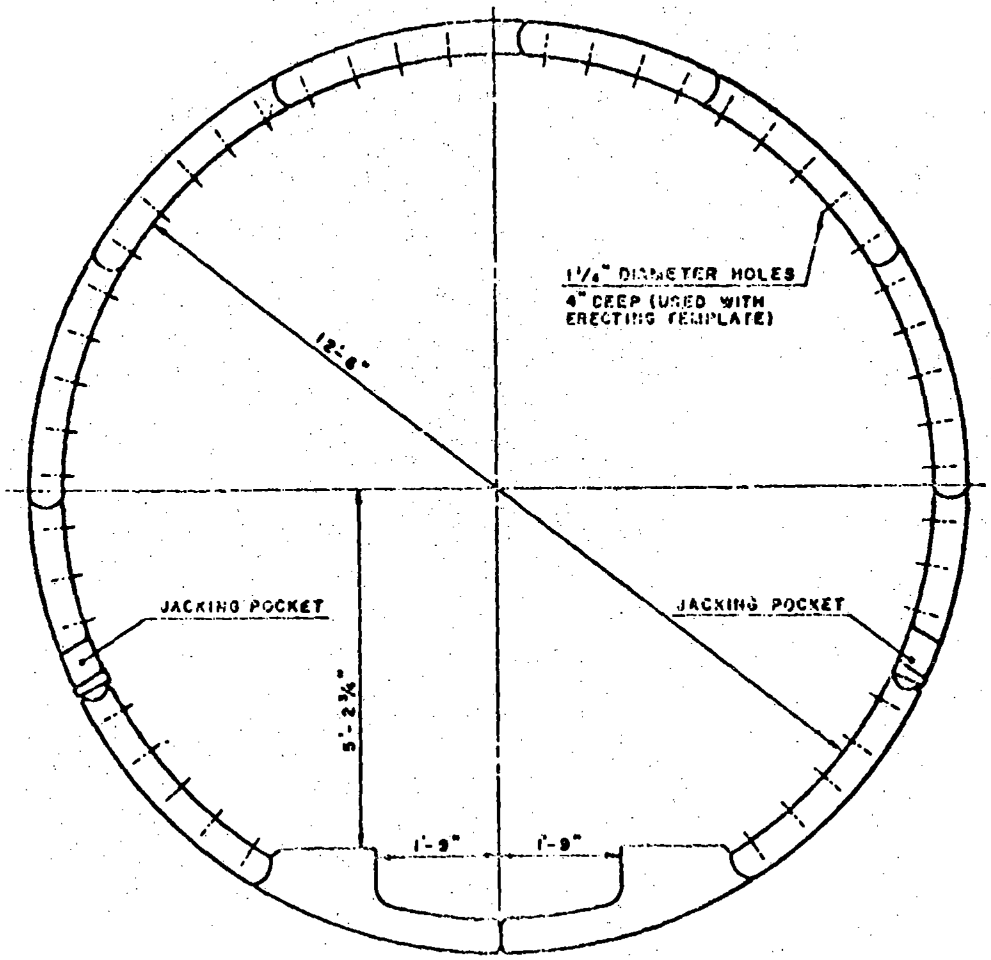


FIGURE 8-9

KNUCKLE-JOINTED CONCRETE SEGMENTS

After Mayo[2]

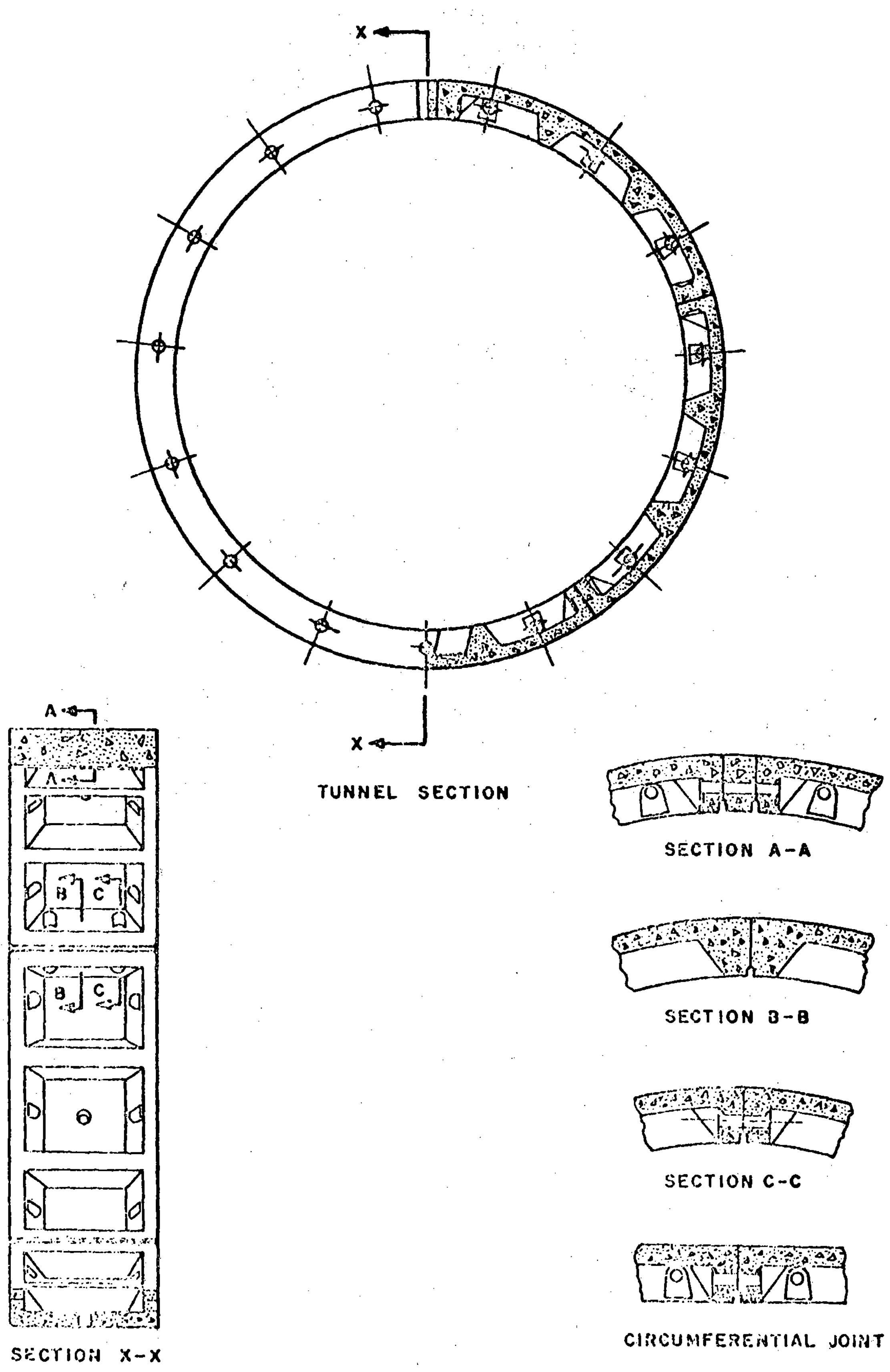


FIGURE 8-10

BOLTED CONCRETE SEGMENTS
After Mayo[2]

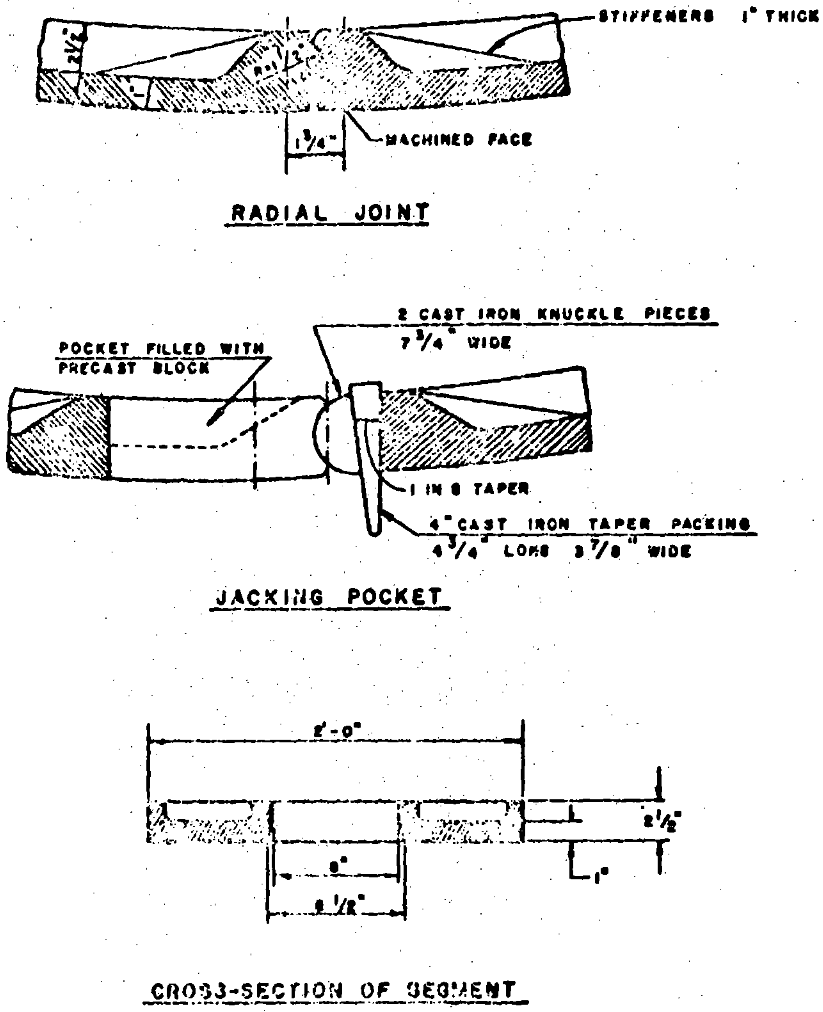


FIGURE 8-11

KNUCKLE JOINTED BOLTLESS CONNECTIONS FOR CAST IRON SEGMENTS

After Mayo[2]

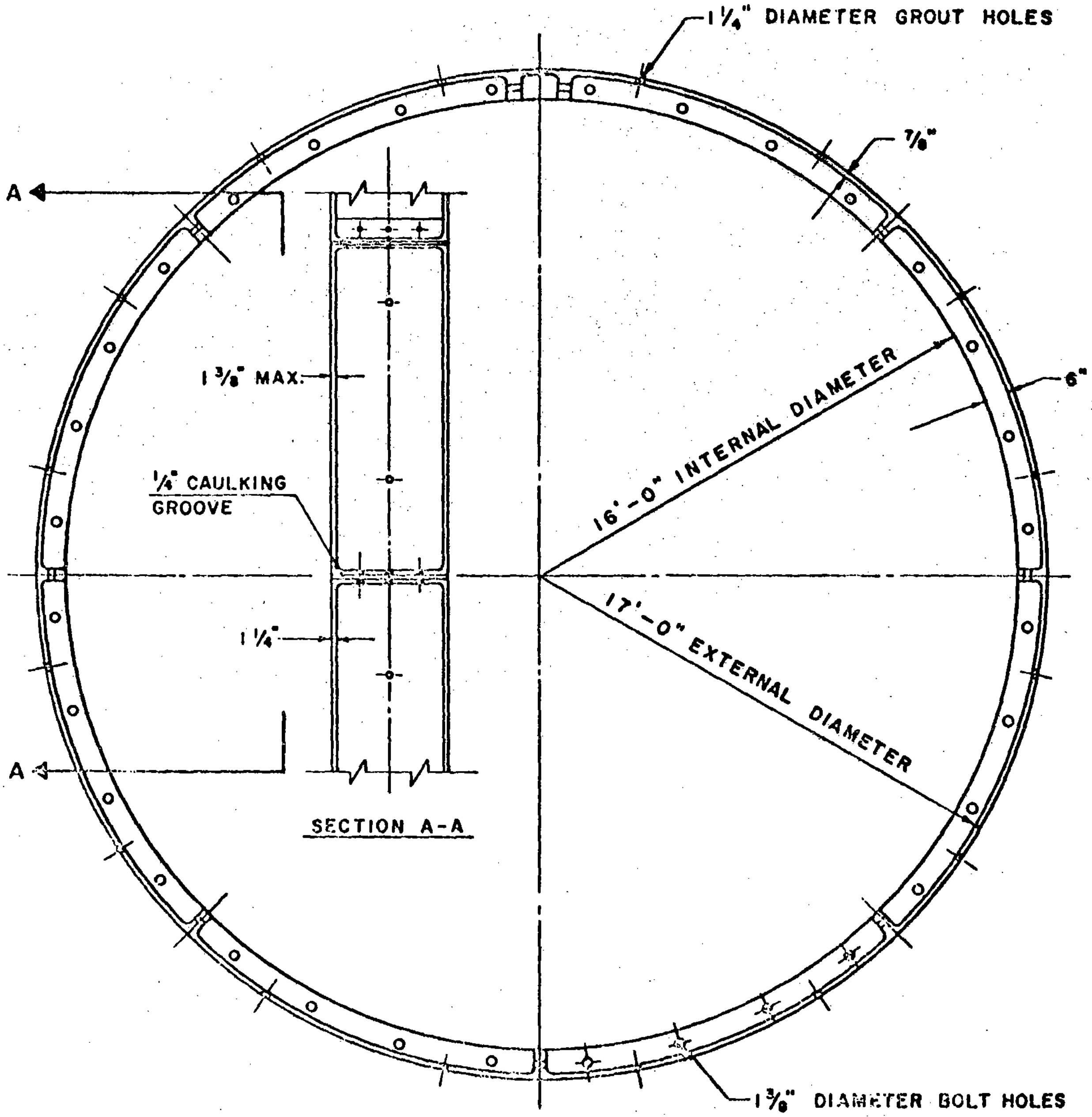


FIGURE 8-12

LIGHTWEIGHT CAST IRON LINER
After Mayo(2)

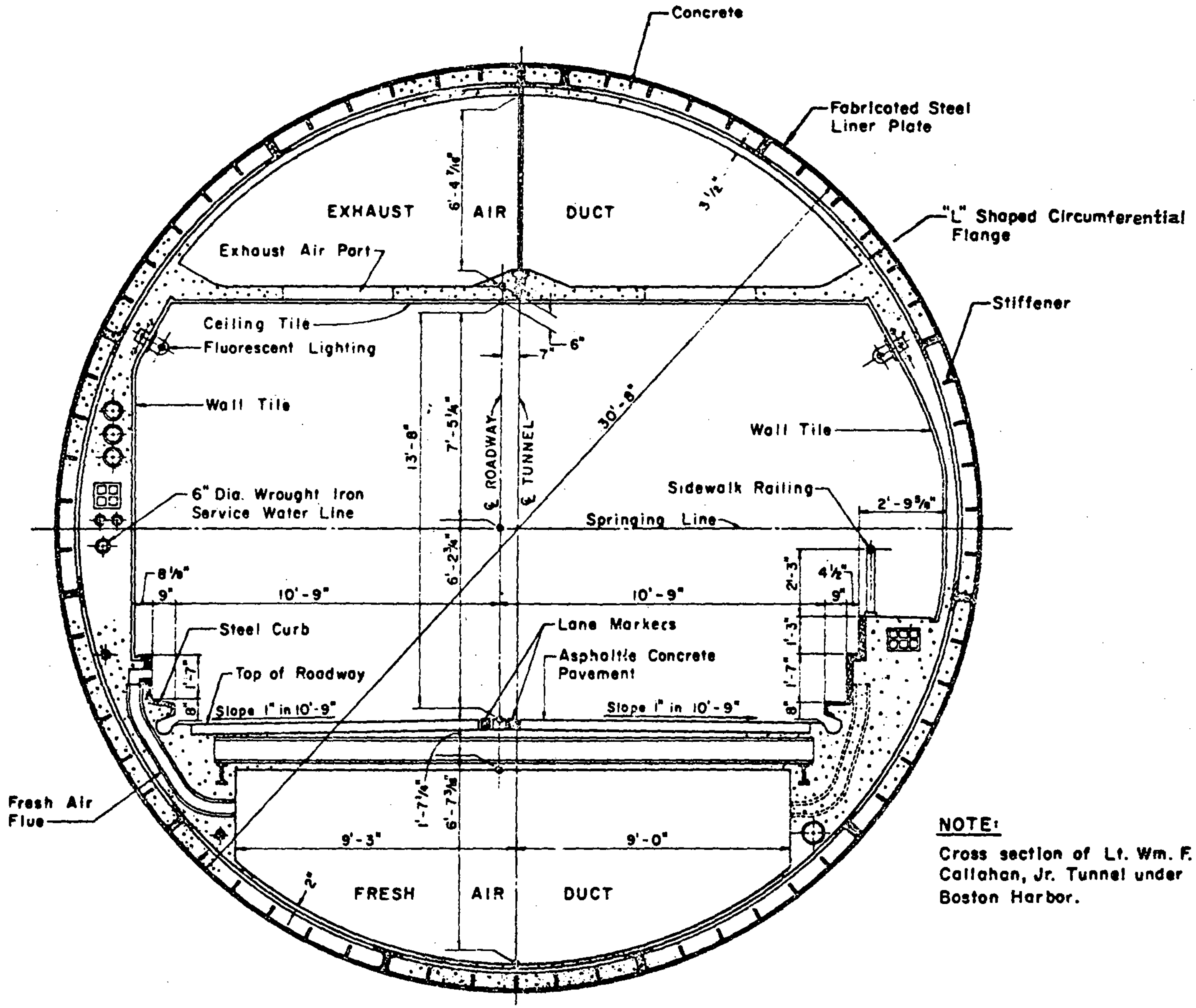


FIGURE 8-13

FABRICATED STEEL LINER PLATE

After Mayo(2)

Knuckle-jointed segments are about 2 feet wide by 6 feet long with a skin thickness of 1 inch and a flange depth of about 2.5 inches. No grouting is required as they are expanded into place.

Regular cast iron segments used in soft ground tunnels have 1-3/8-inch thick skin and 8-inch deep flanges. They weigh about 87 pounds per square foot of external surface including bolts. Grouting is usually used behind cast iron segments having 3/4-inch thick skin and 5- or 6-inch deep flanges weighing about 60 pounds per square foot of external surface including bolts.

Fabricated steel segments are made from structural steel with 1/4-, 1/2-, or 3/4-inch mild steel skin. A curved segment about 9 feet long by 32 inches wide will weigh about 1,500 pounds. Lighter weight pressed steel liner plates are 24 inches wide with 1/4-inch thick skin and flanges on all four edges. They weigh about 16 pounds per square foot of external surface. For tunnel diameters larger than 10 feet, steel ribs are required at alternate rings to stiffen the liner. A secondary concrete liner is required.

PACKING

Packing is the material used to fill the space behind the liner. Normal overbreak by conventional excavation can increase the quantity of concrete by at least 25 percent and sometimes in blocky ground by as much as 100 percent. The excess concrete or packing required for boring is much less. The tailskin void annulus is about 3 inches.

Material used for packing is commonly wet concrete placed by a concrete pump or pneumatic placer, dry concrete, or pea gravel which may be blown through holes in the lagging. Sometimes the pea gravel is then grouted.

Another type of packing is the material used in the joints of liner sections. Asbestos packing and rubber-based Thiokol compound pumped into the joints are typical of these packing materials.

ROCK BOLTS

Rock bolts are steel rods used to lock the individual blocks of rock together and tie the exposed rock back to the undisturbed strata. They are set in holes drilled into the excavation roof and walls. Considerable research is providing better understanding of the art of rock bolting. The economies which can be realized by using rock bolts in place of, or in conjunction with, structural steel ribs provide strong incentive for their use.

There are several types of rock bolts available in both the grouted and ungrouted variety. The grouted bolt is used where the rock is weak and does not have sufficient compressive strength to withstand the pressure of the wedged bolt. The least expensive and most commonly used are the ungrouted wedge type and expansion shell type. Of these, the expanding shell type is most popular because the depth of hole is not critical to locking the bolt in place. If there is danger of rock falling between the rock bolts, steel head boards are used rather than the normal square plate. Wire mesh (typically 4-inch by 4-inch or chain link fencing) may be spread between the rock bolts to catch small pieces spalling from the surface. Examples of three common types of rock bolts are shown in Figures 8-14 and 8-15.

The wedge bolt is usually 1 inch in diameter and threaded at one end and slotted at the other to accommodate the wedge. Although it is available in any length, it is usually used in lengths from 2 to 8 feet. Wedges, driven into the split end of the rod until it grips the sides of the hole, are commonly 3/16 by 3/4 by 5-1/2 inches. A bearing plate or washer and nut are torqued to bear on the rock surface.

The expansion shell type bolt is available in 5/8-inch to 2-1/2-inch diameters; it is available in any length, but is commonly ordered from 4 to 12 feet long. The bolt is tightened against a bearing plate using a power wrench. Rotation of the bolt expands the shell, anchoring it at the bottom of the hole.

Many designs of grouted bolts are available; but, in general, they are of two types: those in which the grout is pumped through the bolt, and those in which a grout-filled sleeve is inserted in the hole and a bolt or rebar is driven through the sleeve to the bottom of the hole. Approximately 0.04 cubic feet of a rise plastic mortar is used for each 5-foot bolt. Grouted bolts, although more expensive, provide more strength in the anchorage.

The number of rock bolts required to support an excavation is largely a matter of opinion about the relative effectiveness of bolts and steel ribs in stabilizing the rock mass. When the amount of one is decreased, a compensating increase in the amount of the other may be made. The method of excavation also affects the amount of support, less being required for boring than for conventional drill and blast which disturbs the surrounding rock to a greater extent.

Typical examples developed by Harza[3] for the quantity of rock bolts required under various rock conditions and excavation methods are shown in Table 8-12.

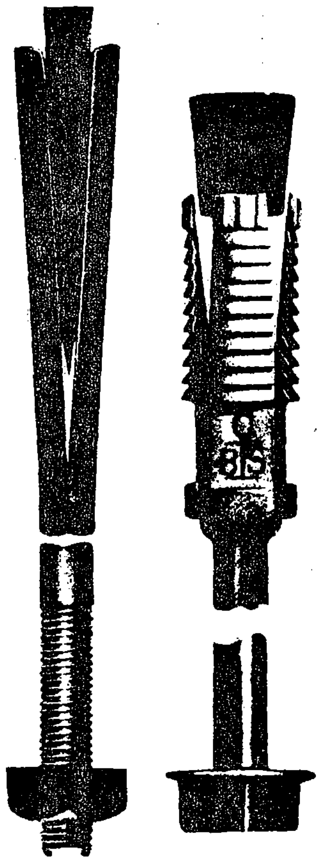
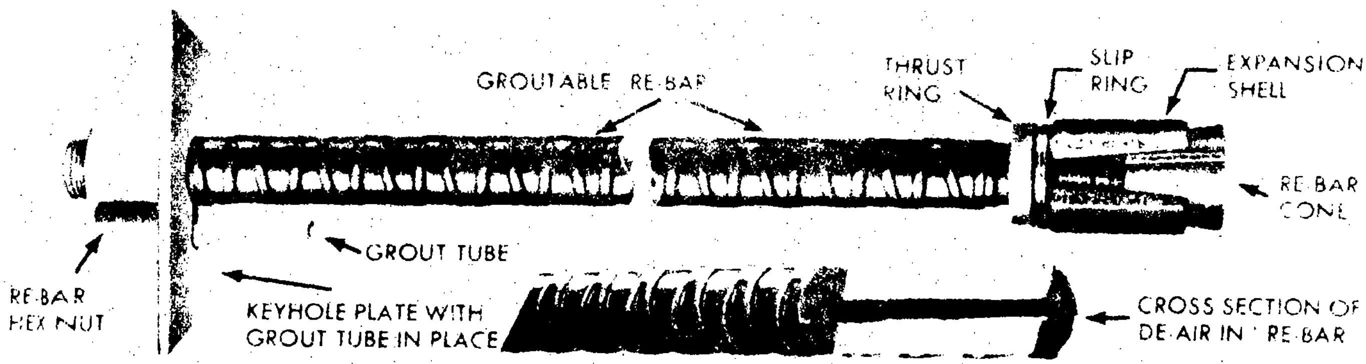


FIGURE 8-14

SLOT-WEDGE AND EXPANSION-SHELL TYPE ROCK BOLTS

After Hair[4]



a. Williams hollow "re-bar"

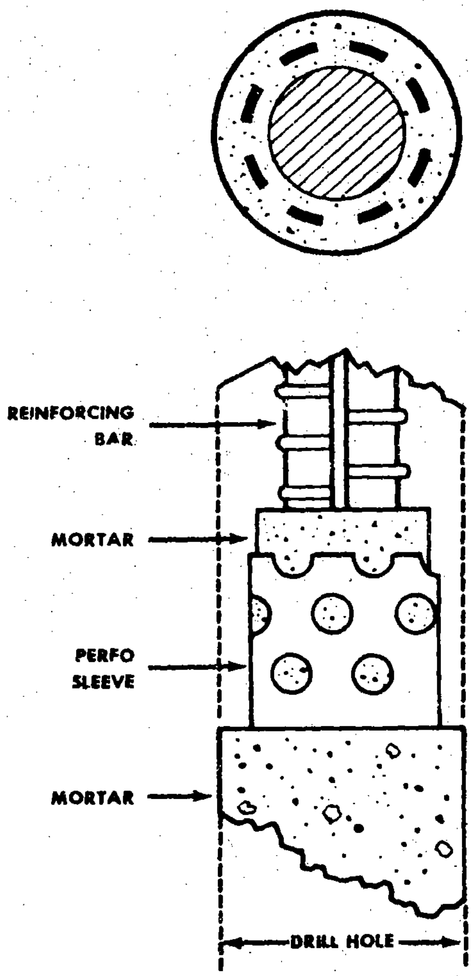


FIGURE 8-15

GROUTABLE ROCK BOLTS

After Hair[4]

TABLE 8-12

ROCK BOLTS AND WIRE MESH IN TUNNELS[3]

Rock Class	Diameter (feet)	Excavation Method			
		Conventional		Bored	
		Spacing	Lbs/Lin Ft	Spacing	Lbs/Lin Ft
I	8	5	12	0	0
	20	5	29	0	0
	30	5	44	0	0
	40	5	58	0	0
II through V	8	3	25	5	12
	20	3	64	5	29
	30	3	95	5	44
	40	3	127	5	58
VI and VII	All	0	0	0	0

The bases for these quantities are:

1. Coverage of 90 degrees of the crown with bolts and wire mesh.

2. Bolts 1 inch in diameter and ten feet long.

3. Mesh 4 inch by 4 inch with No. 6 wire.

4. Spacing as shown in the table.

The table shows the total weight of bolts and wire mesh per linear foot of tunnel.

In selecting the type of ground support, there may be a choice between rock bolts and mesh or steel ribs and lagging.

The selection of ground support method may be made on the following bases:

1. Automation and speed of installation.

2. Differences in amounts of muck to be handled.

The neat line of excavation in the case of rock bolts and mesh will be approximately the same as the interior face of the steel rib. Therefore, excess width must be excavated when supporting a tunnel with steel ribs in order to make room for the steel sets and blocking. In a tunnel of a nominal 20 feet inside diameter, this would amount to at least 1 foot on the radius or 21 percent additional excavation required if using steel sets.

When using a boring machine, much less support is required and the occasional use of rock bolts works well under normal ground conditions.

STABILIZERS AND WATERPROOFING

Chemical grout is used to fill voids and stabilize the ground condition in some situations. In more severe conditions where chemical grout would be too expensive because of the volume required, neat cement grout, a cement-bentonite clay mixture, combinations of cement and sawdust, or any of these combined with chemical grout are used to stabilize the ground or to seal off water flow.

Harza[3] has estimated the quantity of chemical grout required for two water conditions at various depths and the amount of cement grout for conditions of more cavernous nature. Those quantities are given in Table 8-13.

Freezing is used infrequently in tunnel construction due to the expense and time required. When used, the liquid nitrogen which provides a temperature of -320°F is delivered in tank trucks.

Other materials used in waterproofing tunnel construction are sheets of bituminous impregnated cloth, water stops (strip copper, vinyl, or rubber compounds) in concrete joints, and "weepers" made of 4-inch clay pipe through the tunnel wall on 5 to 10-foot centers.

Seepage from low hydraulic heads has been effectively controlled through the application of dry shotcrete using an accelerator for quick set. Under conditions of large volumes of water or mud inflow, bulkheading with sandbags and timber or concrete bulkheads may be required. The quantities of these "special situation" materials are very difficult to estimate even when a specific route is selected. However, the means of providing the required materials to the working zone must be available when the need arises.

SHOTCRETE AND GUNITE

Shotcrete, a mixture of cement, sand, gravel, and water, is applied with a pneumatic spray gun. It is usually placed in 1-inch layers to a thickness of 4 to 6 inches when used as primary lining. In blocky ground, rock bolts or bolts and wire mesh may be used to stabilize the rock before applying the shotcrete.

There are two basic shotcreting processes, referred to here as the dry mix and wet mix processes.

Dry Mix Process

This process consists of the following steps:

1. Cement, aggregate, and damp sand are thoroughly mixed.

2. The cement-sand-aggregate mixture is fed into a special mechanical feeder or gun (referred to here as delivery equipment).

3. The mixture is metered into the delivery hose by a feed wheel or distributor.

TABLE 8-13

CHEMICAL GROUT TAKE[3]
(Gallons of Solution per Linear Foot)

Group	Depth (feet)	Excavated Diameter (feet)			
		8	20	30	40
C	500	2.5	5.0	7.1	9.1
C	1,000	1.2	2.4	3.4	4.4
E	100	120	232	323	417
E	500	100	195	276	352
E	1,000	50	87	139	178
E	2,000	18	35	48	63
E	3,500	15	27	38	49
CEMENT GROUT TAKE[3] (Cubic Feet of Solids per Linear Foot)					
D	100	32	69	101	132
D	500	27	59	86	112
D	1,000	16	35	51	66
D	2,000	7	14	20	28
D	3,500	5	11	15	20

4. This material is carried by compressed air through the delivery hose to a special nozzle. The nozzle is fitted inside with a perforated manifold through which water is introduced under pressure and intimately mixed with the other ingredients.

5. The concrete is jetted from the nozzle at high velocity onto the surface to be shotcreted.

This general process has been used for about 50 years to apply cement and sand mixes in many types of construction. The addition of coarse aggregate is a recent development and gives a much stronger support.

Wet Mix Process

This process consists of the following steps:

1. All of the ingredients, including mixing water, are thoroughly mixed.

2. The concrete is introduced into the chamber of the delivery equipment.

3. The mix is metered into the delivery hose and conveyed by compressed air or other means to a nozzle.

4. Additional air is injected at the nozzle to increase the velocity and improve the gunning pattern.

5. The concrete is jetted from the nozzle at high velocity onto the surface to be shotcreted.

Concrete mixes have been applied by this process on a considerable number of jobs over the past 10 years. Specially designed concrete mixes, with the maximum size of coarse aggregate ranging up to 3/4 inch, have been applied on a few jobs during the past 5 years.

Comparison of Processes

Shotcrete suitable for normal construction requirements can be produced by either process. However, differences in cost of equipment, maintenance, and operational features may make one or the other more attractive for a particular application. Differences in operational features which may merit consideration are given in Table 8-14.

TABLE 8-14

FEATURES OF DRY AND WET MIX SHOTCRETE PROCESSES

Item	Dry Mix Process	Wet Mix Process
1	Control over mixing water and consistency of mix at the nozzle. Better for stopping inflow of ground water.	Mixing water is controlled at the delivery equipment and can be accurately measured.
2	Better suited for placing mixes containing lightweight porous aggregates.	Better assurance that the mixing water is thoroughly mixed with other ingredients. This may also result in less rebound and waste.
3	Capable of longer hose lengths.	Less dust accompanies the gunning operation.

Guniting, a similar technique originally developed for application of mortar or plaster (cement, sand, and water) to surfaces, is normally used 2 to 4 inches thick where minimum earth support is required or for a final finish coating. Fundamentally, however, the only difference between gunite and shotcrete as presently applied is the addition of pea gravel to the mixture.

Shotcrete or gunite is most effective if applied immediately after (within minutes) exposure of the surface. It can be applied by one or two men working from the jumbo or other platform. For additional stability, rock bolts may be installed immediately after the mortar hardens.

Although some attempts to use shotcrete indicate the need for development of improved equipment for application, its supporters claim the technique to be suitable for all rock conditions, including unconsolidated and squeezing ground. If this optimism survives the test of time, the method appears to have a bright future for use as the primary lining and possibly the secondary lining as well. Its speed and safety in application compared to conventional primary lining mark it as a possible solution to the problem of installing earth support at the same rate as excavation.

Normally the ingredients for shotcrete or gunite are mixed by machine close (approximately 800 feet maximum pumping distance) to the point of application. The sand and gravel are transported to the point of mixing in bulk containers. The cement may be transported in bulk or in standard 1-cubic-foot paper bags weighing approximately 94 pounds. To increase the rate of application, the sand, gravel, and cement may be premixed outside the excavation and transported as dry bulk to the point of application where the necessary water is added. Water is provided by a pipeline extended from outside the excavation. Compressed air is provided either by a compressed air line from a compressor outside the excavation or an electric or diesel compressor in the application area.

The point of application may vary from immediately behind the heading to several hundred feet back depending on the use (primary support, water seal, etc.) and the ground conditions. In a continuous operation, the distance between the heading and point of application will need to be maintained more or less constant as the working face advances.

MISCELLANEOUS AUXILIARIES

Many small miscellaneous auxiliary pieces of various sizes and shapes are used depending on the type of support. For example:

- Clip angles for attaching spreaders
- Lagging clamps, 3 by 5 by 3/8 inches, weighing 1.5 pounds

- Carriage bolts, 3/4 inch
- Crown bar hangers

These parts are either installed on the rib pieces at an external assembly area or transported to the working zone in shipping crates.

Pins used for temporary support of wall plates are 1-inch rods about 4 feet long. They can be banded into bundles or crated for transport to the working zone.

LINING FORMS

The forms for placing the concrete liner, if cast-in-place lining is used, may be wood or steel. Reusable steel forms are more economical and present less materials handling problems for long lengths of tunnel. These are left in place until the necessary strength is achieved by the concrete and then moved ahead to the current point of liner placement. Special equipment is required to effectively handle the large form sections.

SPECIAL SITUATIONS

Special situations which may cause considerable difficulty in rock support or excavation, thus slowing the rate of advance, are squeezing ground, swelling ground noncohesive ground, excessive rates of water flow under high pressure, corrosive water, high rock temperatures, or rock burst conditions due to residual stresses.

Squeezing ground exerts pressure on the tunnel supports from all sides, tending to close the excavated space. When this condition is present, it is desirable to use full-circle support to obtain the greatest possible strength per pound of material used, and to lag continuously and thoroughly back-pack with dry gravel or dry concrete to obtain uniform load distribution. The dry pack is sometimes grouted, or wet concrete is used. It has been observed that a pound of steel support in the form of a full-circle rib will carry almost twice the load it will carry as a straight leg rib.

Swelling ground may be supported in the same manner as squeezing ground if the swelling capacity is moderate. If the rock has a high swelling capacity, it may be desirable to provide a means for long-term expansion of the ground into the excavated space. Present practice is to provide some form of crush lattice (usually white pine blocks as shown in Figure 8-16) in the rib sets to prevent failure of the ribs. Yielding lagging between the ribs is also used to allow the rock to squeeze into the tunnel space between the ribs. Additional excavation between the ribs is sometimes used to "soften" the ground, causing it to extrude between the ribs

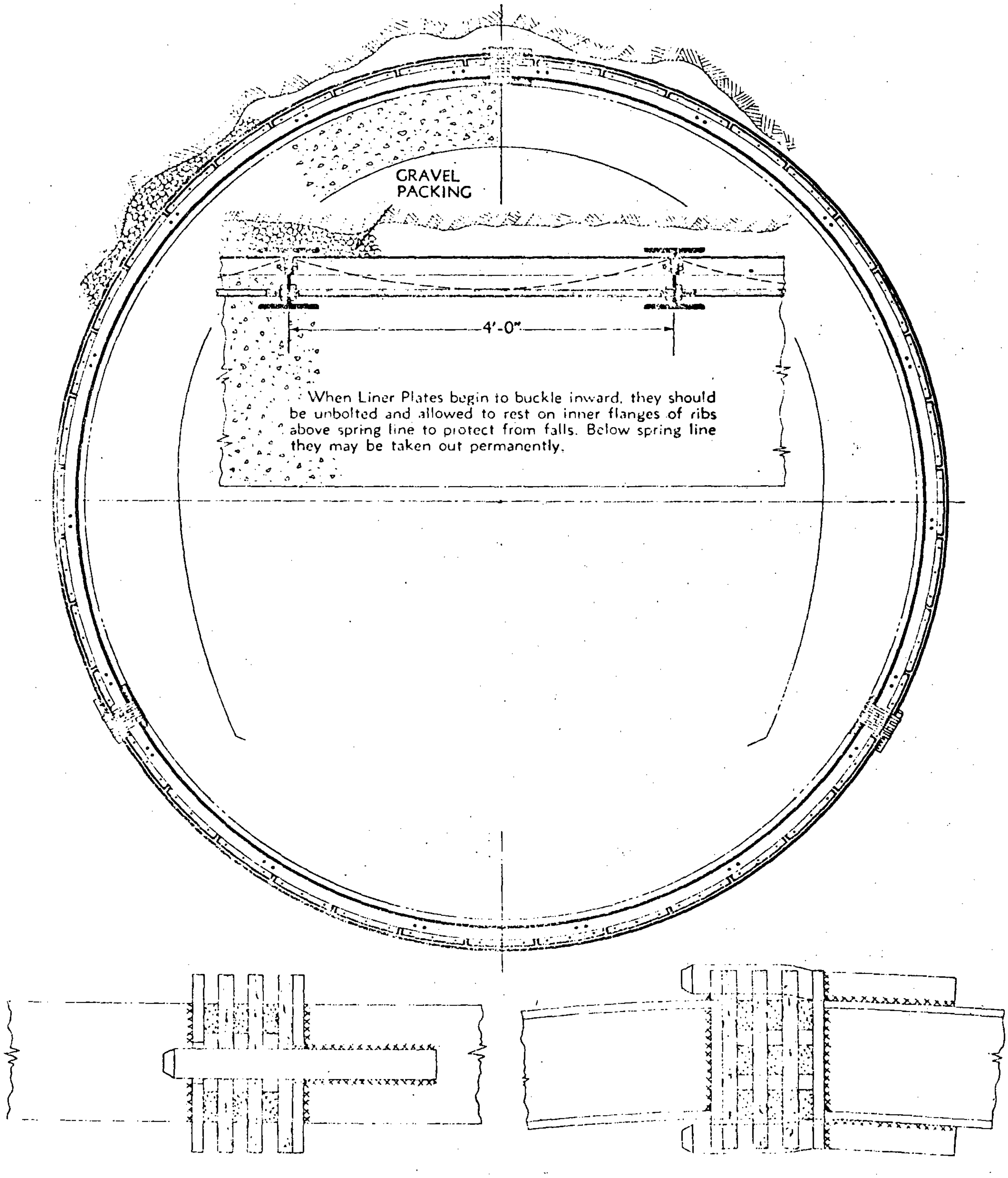


FIGURE 8-16

CRUSH LATTICE FOR YIELDING SUPPORT

After Proctor and White[1]

until the swelling forces have been balanced by establishing ground cylinder action. If this situation is encountered, the swelling ground and gravel back-packing produce muck for an extended period of time and at a considerable distance back of the excavation face. This muck must be entered into the muck transport system for removal or be removed by some other method. Lagging removed to allow the ground to swell must be moved forward to the current point of support installation or, if unusable, removed from the tunnel as scrap.

When very bad or noncohesive ground is encountered in a full face or mixed face situation, the forepoling excavation technique may be used. This is a very slow process in which wood or steel spiles are driven individually into the face above the leading rib set to support the crown while the face is advanced to the position of the next rib set. Wood spiles are usually 3 by 6, 4 by 6, or 6 by 6 timbers, approximately 10 feet long and wedged on one end. The common steel spiles are 10-foot lengths of 6- or 10-inch channel.

Where rapid means of excavation are used in unconsolidated ground, a full shield is required. This is a steel cylinder, of the full tunnel diameter, with spiling plates on the front which are jacked ahead by hydraulic rams. The face may also be shielded and muck mined selectively through windows as the shield is advanced. In order to keep out excess water, it may be necessary to work under compressed air, moving men and materials through air locks.

Where flows of water under high pressure are encountered at depth, face conditions for mining may become very difficult. Panning of water, freezing, and/or grouting may be the only way to advance. Under these conditions, mechanical excavation could be impossible.

Corrosive water is a special situation of hazard because of the rapid deterioration of steel tunnel sets, concrete, transport guideways, and all equipment. Asphalt coatings may be applied to steel sets and liner plates, while every precaution is taken to prevent excessive contact between water and equipment.

In some deep conditions, residual stresses in the rock may cause rock bursts. These may be sudden failures of large areas without warning. In modern practice strain gauges are used to predict danger areas which would then receive additional support or linings to prevent such failure. This would require transport and offloading of special ground support materials at intermediate points behind the normal offloading point in the near-face zone.

"Crown bars" and "truss panels" are structural members used for temporary support in special situations at the working face with difficult ground. Since they are reusable, they are handled primarily in the zone of the working face once they have been transported from the assembly area to the working face. When they are no longer needed they may be removed to a shaft station or other area for storage. Crown bars may be fabricated from double channels welded together to form a box beam. They are used to provide early support for the crown when working in weak ground. A typical crown bar is 12 by 12 inches in section and 10 to 15 feet long.

Truss panels are fabricated temporary support members sometimes used with the heading and bench method of advance in lieu of crown bars. They are attached to the ribs for a distance of one or more ribs ahead of the bench shot. They are left in place until posts are installed and then are removed and sent ahead to be reused at the working face.

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1. Proctor, R. V. and T. L. White, "Rock Tunneling With Steel Supports," The Commercial Shearing & Stamping Co.; includes "Introduction to Tunnel Geology" by Karl Terzaghi, 1946.

2. Mayo, R. S., "Tunneling, The State of the Art," Robert S. Mayo & Associates, PB 178036, January 1968.

3. Harza Engineering Company, "High-Speed Ground Transportation Tunnel Design and Cost Data," PB 178201, March 1968.

4. Hair, J. L., "Construction Techniques and Costs for Underground Emplacement of Nuclear Explosives," U. S. Army Engineer District, PNE-5004F, April 1969.

CHAPTER 9

MATERIALS FOR SYSTEMS EXTENSION

The systems which must be extended in pace with the advancing tunnel face are, in addition to the ground support system described in Chapter 8,

- The horizontal material transport system consisting of one or more modes of transport.

- The support service systems including ventilation, compressed air, service water, ground water removal, and lighting and power.

Modes of material transport applicable to the horizontal attitude are trucks, conventional rail systems, monorail systems, siderail systems, conveyors, and hydraulic or pneumatic pipelines. These transport modes are described in Chapters 3 and 4.

The materials or substances handled by the support service systems are described in Chapter 11. The flow rate of these substances determines the system size which, with the tunnel advance rate, determines the rate at which materials must be transported to the near face zone to extend the support service systems.

MATERIAL TRANSPORT SYSTEMS

Truck and Conventional Rail

For trucks and conventional rail equipment, roadbeds or rail beds are needed. A finished roadbed can be achieved by paving or by consolidating and compacting the surface materials with additives. In view of the advance rates and transit distances considered in this study, it seems reasonable to expect average in-transit speeds for rail and truck systems in the range of 20 to 40 miles per hour. To support this speed range, rail beds or roadbeds must meet rigid design specifications and considerable care must be taken in their construction to ensure stability and durability.

Beds are assumed to be constructed in either one of two ways:

- Ballast can be laid on the floor of the tunnel to provide the basic foundation.

- Platforms can be emplaced on the floor of the tunnel and attached to the ground support for alignment and structural integrity.

The ballast material is assumed to be loose dry gravel weighing 95 pounds per cubic foot. Muck is not assumed to be used because of its variable nature and unknown stabilization characteristics. If it is found on a particular project that the muck produced from all or a portion of the tunnel is suitable for ballast, the need for inbound transport of ballast could be eliminated and the outbound muck transport rate would be reduced up to 5 percent of the total for those portions of the tunnel producing usable muck. Platforms are assumed to be constructed of welded or bolted steel beams. The transport rates of ballast and platforms required to extend the rail or roadbed at various advance rates are summarized and compared in Figure 9-1 to the muck rates.

To derive the quantities of extension materials involved in providing rail beds or roadbeds, it is assumed that two-way traffic facilities are always required, that is, double track or two-lane roads. It is also assumed that the clearances required for rail systems are equivalent to those for truck systems. The dimensions used are shown on Figure 9-2. For the 30-foot and 40-foot tunnels, it is assumed that standard rail cars, track gauges and spacing, and track accessories are used. The dimensions used in the 20-foot and 10-foot tunnels involve nonstandard or narrow gauge rail equipment. Two bore configurations are assumed; vertical sidewall and circular. Platforms are not considered for the vertical sidewall configuration.

To determine the bed requirements, the appropriate equipment cross-sectional spans are fitted into the vertical sidewall and circular bore configurations. For the vertical sidewall, little or no problem is encountered in laying the span within the configuration as shown in Figure 9-3. For the circular bore, however, a serious problem is encountered. The span will fit only when raised some distance from the tunnel invert as shown in Figure 9-4. For the 40-foot tunnel this distance is 3 feet. A cross-sectional area is thus created which must be filled with ballast or bridged by platforms. The volume and mass transport rates of ballast required to fill the volume established by this area and various tunnel advance rates are shown in Table 9-1. Also shown are the ballast requirements for the vertical sidewall configuration. The numbers in parentheses adjacent to the tunnel diameters represent the pounds of ballast required per linear foot of tunnel for the circular and vertical sidewall configurations.

These volume and mass rates represent the quantities of ballast required for a roadbed. For the rail bed, the quantities of ties, rails, and accessories must be added to the ballast requirements. These are shown in Table 9-2 and were determined from the nomograph on Figure 9-5 for the basic assumptions indicated.

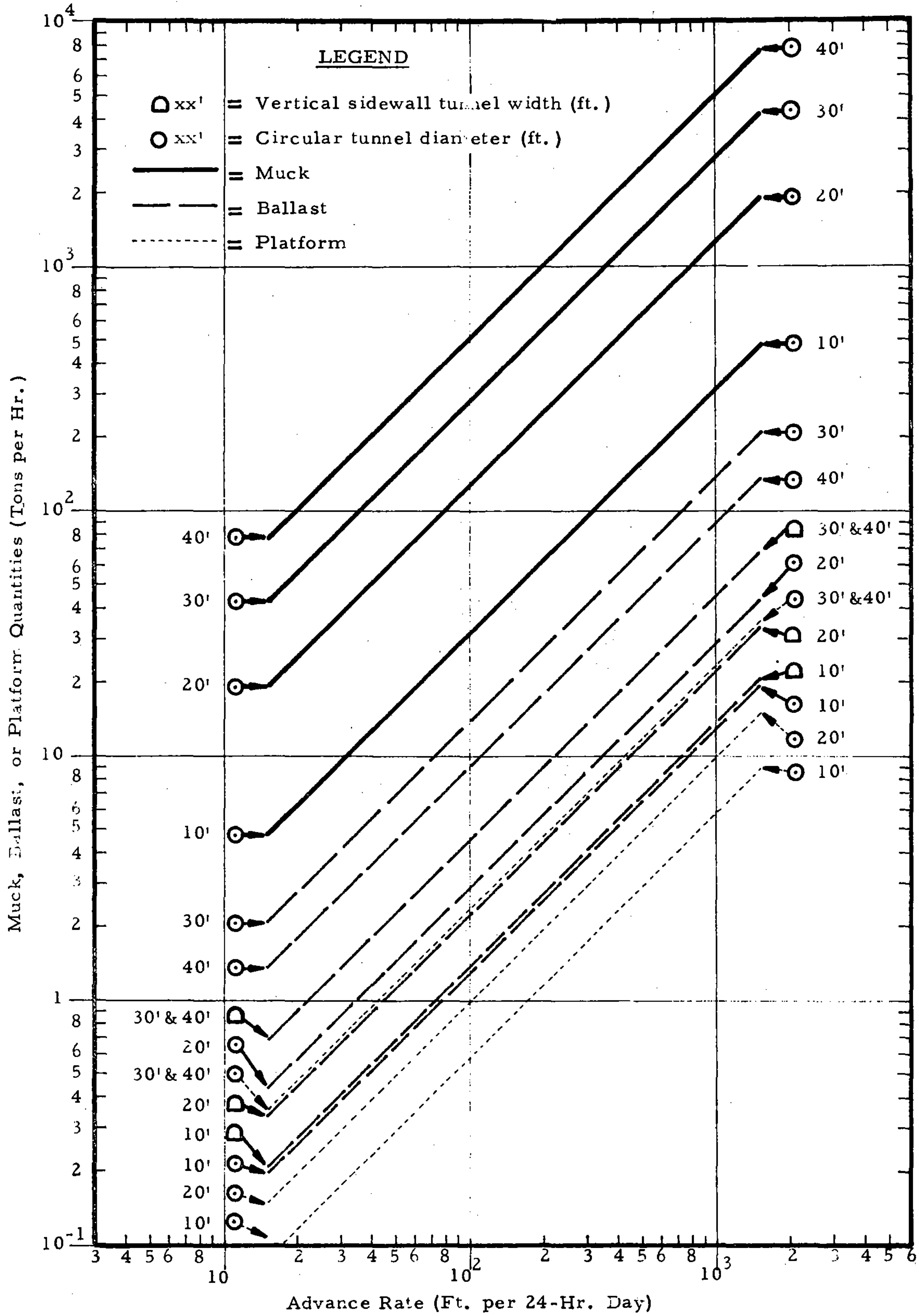
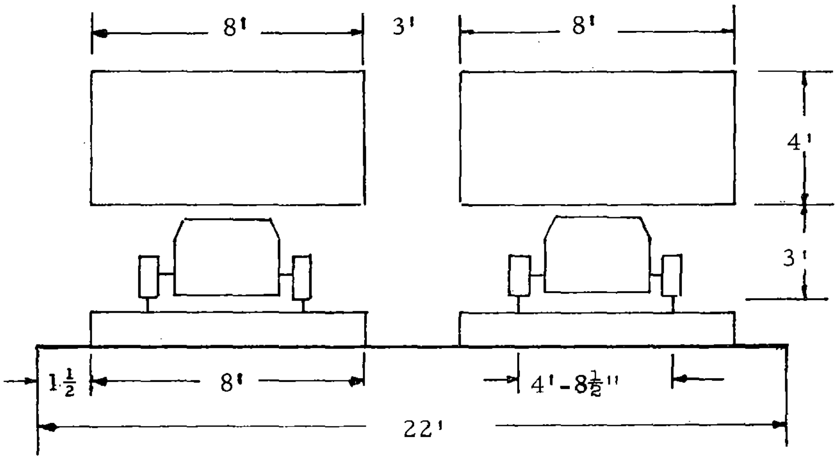


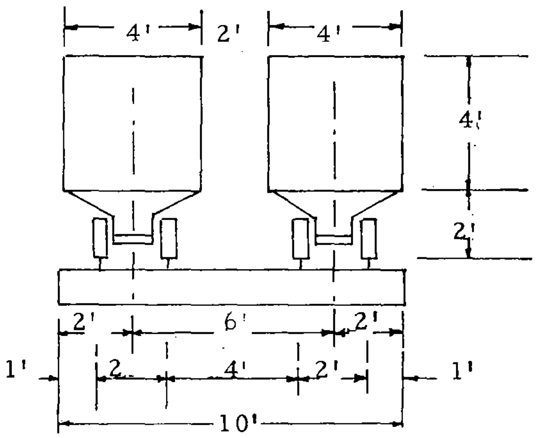
FIGURE 9-1

COMPARISON OF MUCK, BALLAST, AND PLATFORM QUANTITIES

30- and 40-Foot Tunnel
(Standard)



20-Foot Tunnel
(Special)



10-Foot Tunnel
(Special)

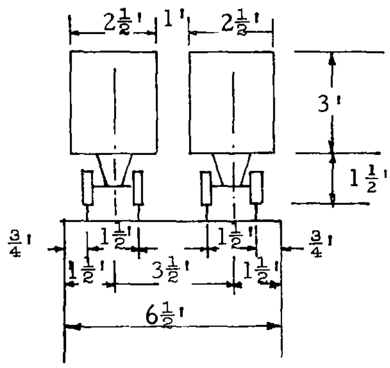


FIGURE 9-2

CONVENTIONAL RAIL SYSTEM DIMENSIONS

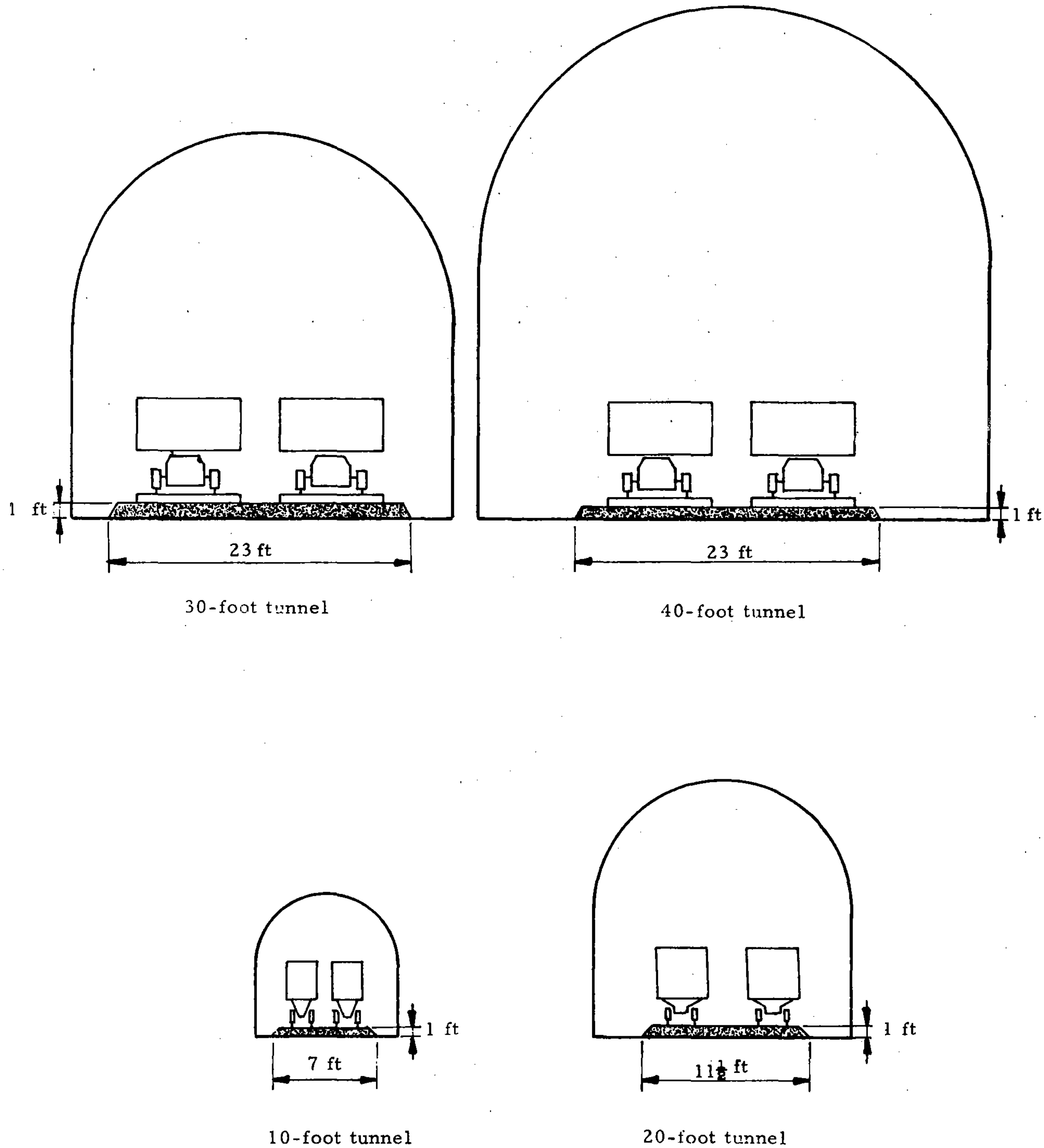


FIGURE 9-3

GEOMETRY OF ROADBED SPANS
Vertical Sidewall Tunnels

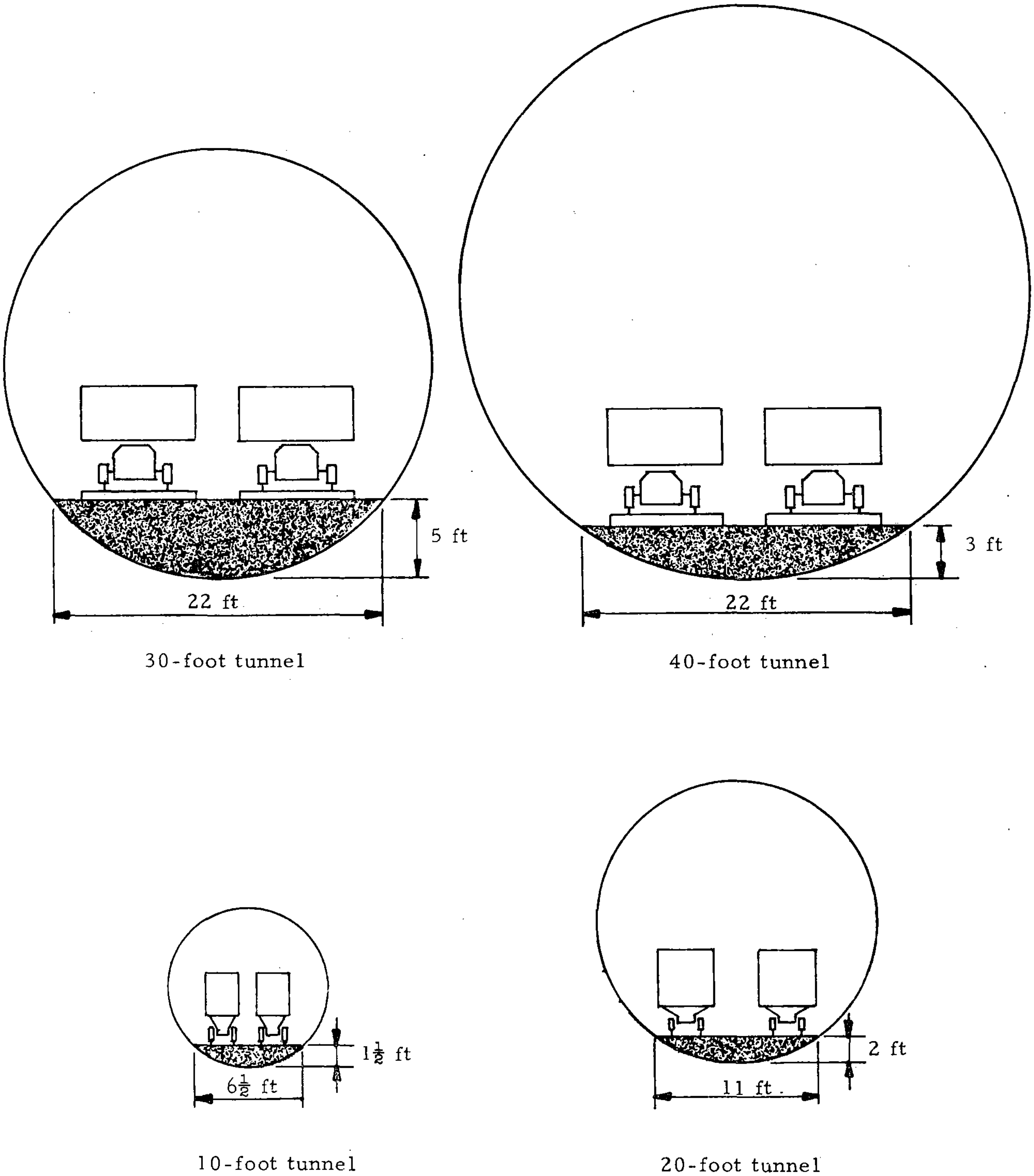


FIGURE 9-4

GEOMETRY OF ROADBED SPANS
Circular Tunnels

TABLE 9-1

BALLAST REQUIREMENTS

Advance Rate (ft/day)	Tunnel Diameter (Feet): 10				20				30				40			
	Circular (655 lb/ft)		Vertical Sidewall (672 lb/ft)		Circular (1,490 lb/ft)		Vertical Sidewall (1,120 lb/ft)		Circular (7,000 lb/ft)		Vertical Sidewall (2,950 lb/ft)		Circular (4,480 lb/ft)		Vertical Sidewall (2,950 lb/ft)	
	CYH	TPH	CYH	TPH	CYH	TPH	CYH	TPH	CYH	TPH	CYH	TPH	CYH	TPH	CYH	TPH
300	3.5	4.1	3.3	4.2	7.3	9.3	5.4	6.9	34.0	43.6	10.7	13.7	22	28.0	10.7	13.7
500	5.0	6.4	5.4	6.9	10.3	14.5	8.9	11.4	50.8	65.4	17.8	22.8	34	43.6	17.8	22.8
750	7.5	9.7	8.1	10.4	16.9	21.8	13.3	17.1	84.8	105.0	26.6	34.2	51	65.4	26.6	34.2
1,500	15.0	19.4	16.2	20.8	33.8	43.6	26.6	34.1	169.6	210.0	53.2	68.2	102	130.8	53.2	68.2

NOTES

1. Ballast material is loose, dry gravel at 95 lb/ft^3 or 1.282 T/yd. Numbers in each CYH column denote the cubic yards per hour of ballast required. Numbers in the TPH column are the ballast tons per hour.
2. Ballast for circular tunnels based on the cross section area equation $A = 2\frac{\ell h}{3}$, where ℓ = chord length and h = height of chord. The chord lengths correspond to the span dimensions indicated in Figure 9-2; h is the height above the floor that is required in order to fit the chord length into the cross section.
3. Sidewall calculations are based on the required chord lengths and an assumed constant thickness of ballast 1 foot. For the 30- and 40-foot tunnels 1/2 foot is added to each end of the chord width making a total span of 23 feet in lieu of 22 feet used in the circular case. For 20 feet and 10 feet, 3 inches are added to each end of the chord length making a total of 11-1/2 feet and 7 feet, respectively.
4. These ballast requirements are all for double lane or track systems.
5. For circular tunnels, the heights above the tunnel floor required to fit in span needed for rail system are: 10 ft - 1-1/2 ft
   20 ft - 2 ft
   30 ft - 5 ft
   40 ft - 3 ft

TABLE 9-2

QUANTITIES OF TIES, RAILS, AND ACCESSORIES

Material Rate, Tons/Hour

Advance Rate (ft/day)	Item	Tunnel Diameter			
		10 feet (139 lb/ft)	20 feet (165 lb/ft)	30 feet (240 lb/ft)	40 feet (240 lb/ft)
300	Rails and Accessories	0.54	0.54	0.84	0.84
	Ties	0.33	0.48	0.66	0.66
	Total	0.87	1.02	1.50	1.50
500	Rails and Accessories	0.92	0.92	1.38	1.38
	Ties	0.56	0.84	1.12	1.12
	Total	1.48	1.76	2.50	2.50
750	Rails and Accessories	1.34	1.34	2.16	2.16
	Ties	0.83	1.24	1.66	1.66
	Total	2.17	2.58	3.82	3.82
1,500	Rails and Accessories	2.70	2.70	4.16	4.16
	Ties	1.66	2.49	3.32	3.32
	Total	4.36	5.19	7.48	7.48

NOTE

Tonnages are obtained from the nomograph in Figure 9-5 for 30- and 40-foot tunnels; 90 lb/yd ASCE, rail is assumed coming in 33-foot sections. For 10- and 20-foot tunnels, 60 ASCE in 30-foot sections is assumed.
Railroad tie density assumed = 30 lb/ft^3 ($\approx$ southern cypress)

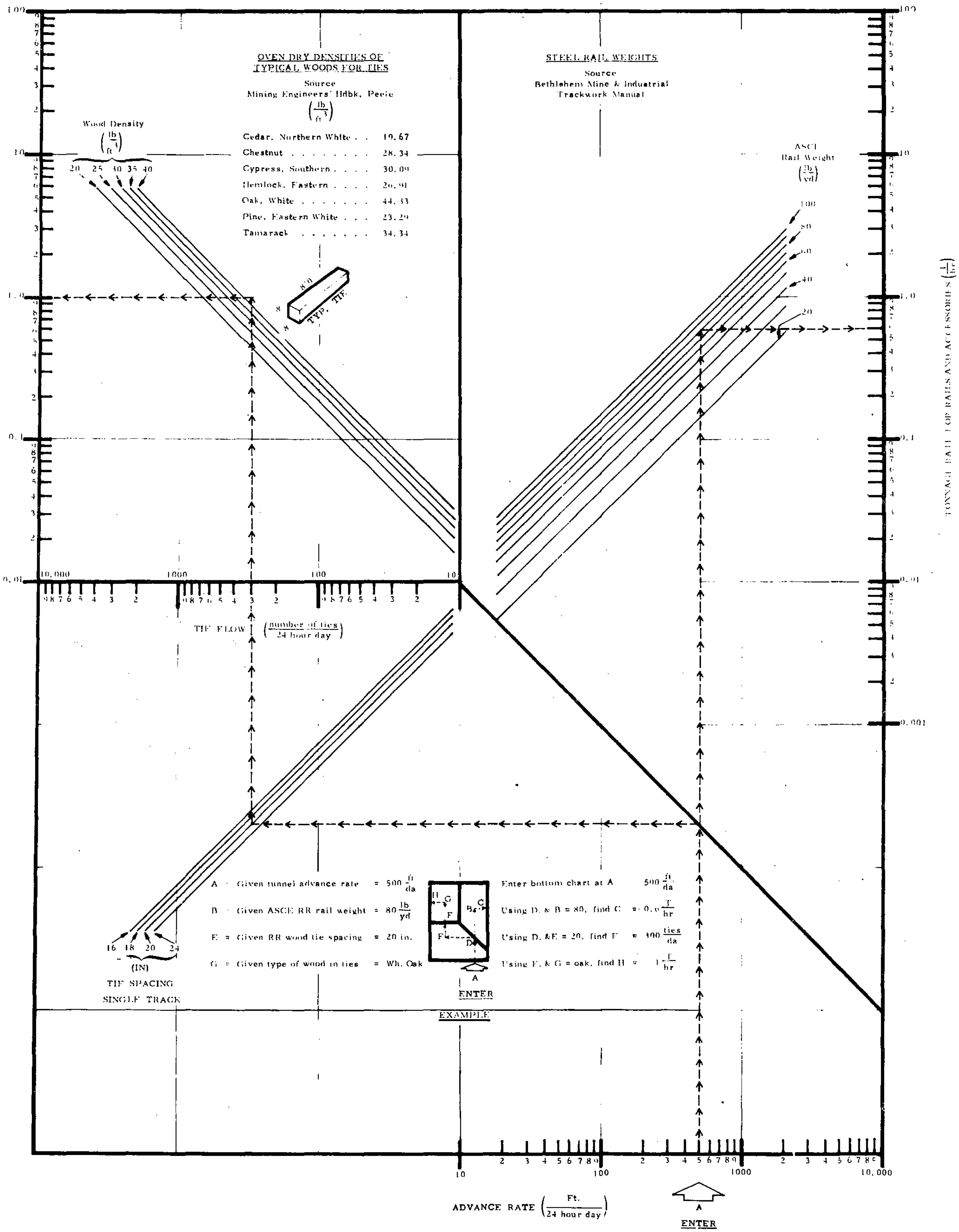


FIGURE 9-5

QUANTITIES OF TIES, RAILS, AND ACCESSORIES

For platforms, the required quantities are based on the double-track platform shown in Figure 9-6. The dimensions and beam sizes shown are for the 30-foot and 40-foot tunnels. These were scaled down for the 10-foot and 20-foot tunnels with the exception of the platform length which was held constant at 8 feet. For rail systems, the platform may have attached rails, in which case the emplacement of the platform would also accomplish the tracklaying effort. The quantities of platforms required to support the advance rates and circular tunnel sizes are shown in Table 9-3.

Platforms are not assumed to be used in vertical sidewall tunnels. However, it is possible that they can be effectively used here as well. An alternate method would be to have heavy beams spanning the bottom of the configuration. In some cases these beams are required for ground support. Another alternative would be to pour concrete floors. If this approach is used, the material quantity rates for concrete would be slightly greater than those estimated for ballast.

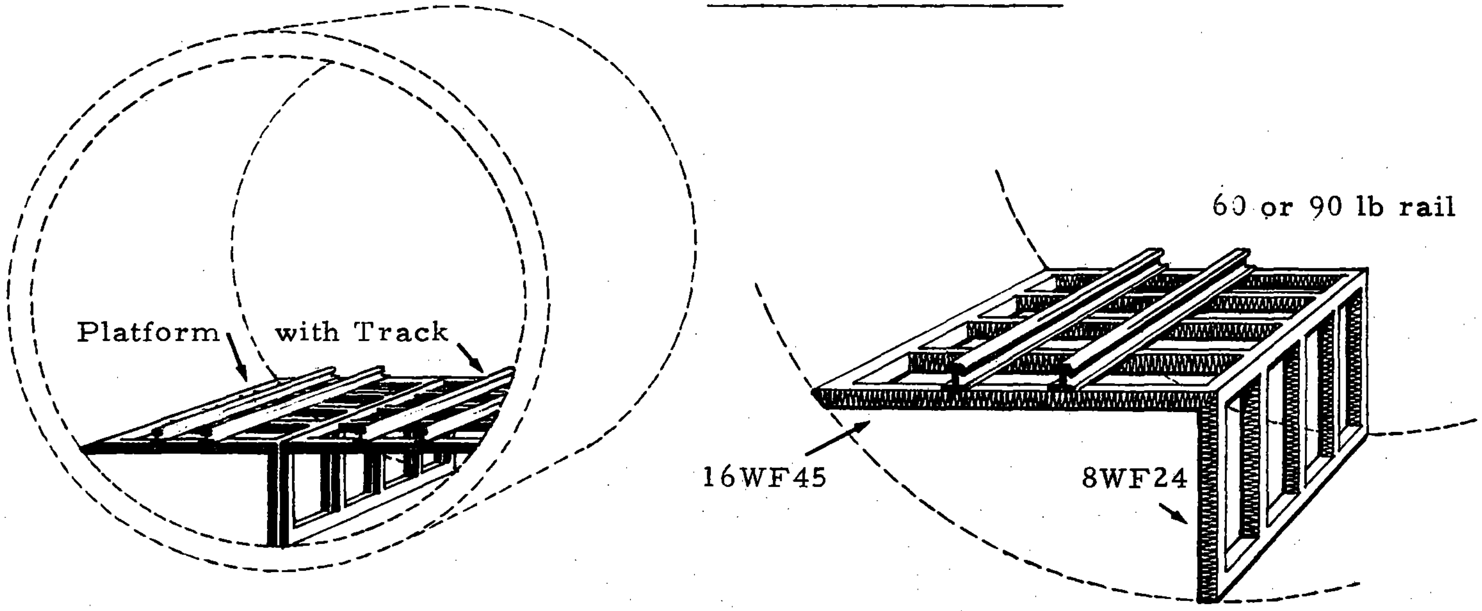
Monorail

Two approaches for support of a monorail system are considered. The concept shown in Figure 9-7 supports the monorails from structural members attached to every fourth ground support rib set. These rib sets are increased in size to carry the additional load imposed by the monorail system. The quantities in Table 9-4 include only the increased amount of steel in these double-duty rib sets. The other concept for which quantities are shown in Table 9-4 supports the same structural members directly from the tunnel wall and roof by means of rock bolts. Many other design concepts could be developed to support the monorails at various elevations and for various module sizes. For those concepts which transmit the load to the tunnel floor by means of structural steel supporting members, the quantity of structural support material per foot of tunnel length will increase as the elevation of the monorail or the module size increases. No attempt was made to optimize the concepts used to derive the order of magnitude material rates presented in Table 9-4. Data in this table include the monorails, support members, miscellaneous steel and rock bolts or the portion of the support ring due to the load imposed by the monorail system.

Siderail

The siderail modules travel on wide flange beams supported from the tunnel floor or walls by structural support members. A typical arrangement for a single track guideway is shown in Figure 9-8. The data in Table 9-5 are order of magnitude quantities for a double system of this support concept which has not been optimized for a tunnel environment. The quantity of support material per foot of tunnel will increase with the height above the floor and the module size.

CIRCULAR TUNNELS



For 30-and 40-Foot Tunnels (covers ≈22-foot span)

1/2 Platform Weight	=	4,000 Pounds
1 Track Weight (90 lb)	=	480 Pounds
Total 1/2 Platform Weight	=	4,480 Pounds or 2.24 Tons
Total Platform Weight	=	4.5 Tons

For 20-Foot Tunnels

Estimated Total Weight	=	1.9 Tons

For 10-Foot Tunnels

Estimated Total Weight	=	1.1 Tons

FIGURE 9-6

PLATFORM DESIGN

TABLE 9-3

QUANTITIES OF PLATFORMS

Advance Rate (ft/day)	Tunnel Diameter							
	10 feet (278 lb/ft)		20 feet (476 lb/ft)		30 feet (1,130 lb/ft)		40 feet (1,130 lb/ft)	
	UPH	TPH	UPH	TPH	UPH	TPH	UPH	TPH
300	3.2	1.7	3.2	3.0	3.2	7.2	3.2	7.2
500	5.2	2.9	5.2	4.9	5.2	11.6	5.2	11.6
750	7.8	4.3	7.8	7.4	7.8	17.2	7.8	17.2
1,500	15.7	8.7	15.7	14.9	15.7	35.2	15.7	35.2

NOTES

1. UPH = units per hour; TPH = tons per hour.
2. Quantities based on platform design shown in Figure 9-6.
3. Length of platforms is 8 feet for all tunnel diameters.

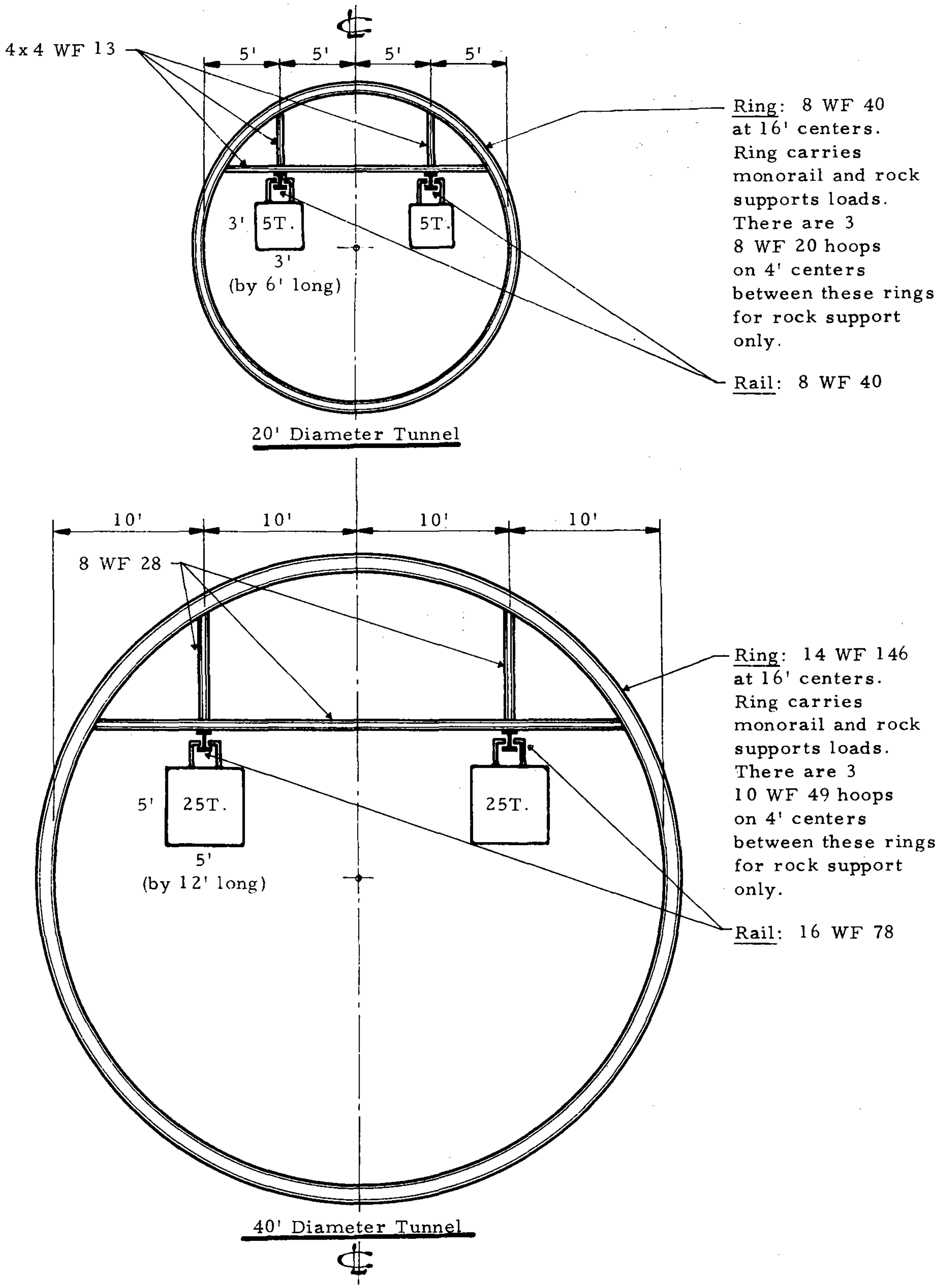


FIGURE 9-7

MONORAIL SUPPORT STRUCTURE

TABLE 9-4

MONORAIL SYSTEM SUPPORT EXTENSION

Material Rate, Tons/Hour

Advance Rate (ft/day)	Tunnel Diameter, Feet							
	10		20		30		40	
	Bolts	Ring	Bolts	Ring	Bolts	Ring	Bolts	Ring
	107 lb/ft	125 lb/ft	150 lb/ft	200 lb/ft	215 lb/ft	425 lb/ft	290 lb/ft	930 lb/ft
300	0.67	0.78	0.94	1.3	1.4	2.7	1.8	5.8
500	1.1	1.3	1.6	2.1	2.2	4.4	3.0	9.7
750	1.7	2.0	2.3	3.1	3.4	6.6	4.5	14.0
1,500	3.7	3.9	4.7	6.3	6.7	13.0	9.1	29.0

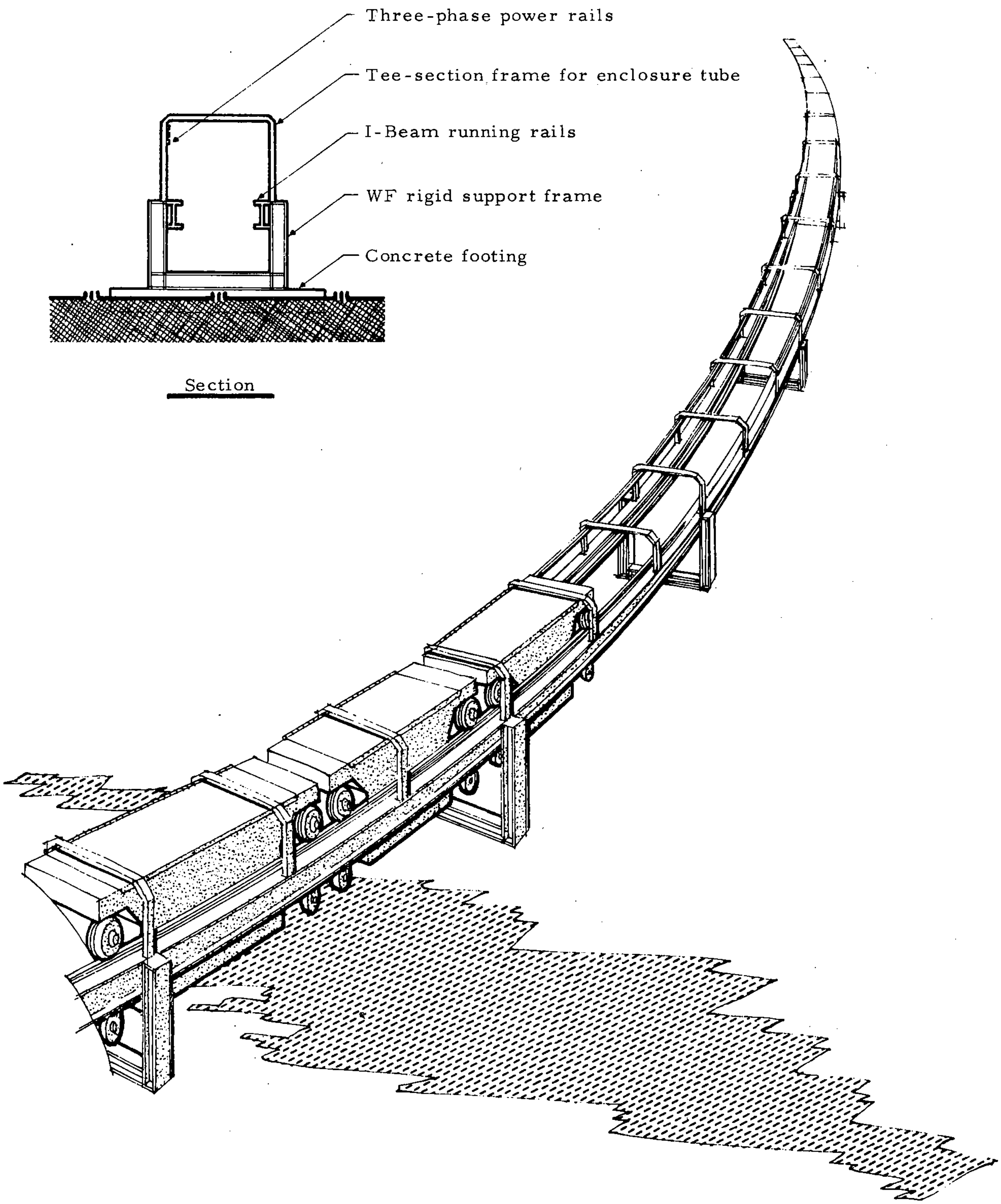


FIGURE 9-8

SIDERAIL SYSTEM SUPPORT

TABLE 9-5

SIDERAIL SYSTEM SUPPORT EXTENSION
Material Rate, Tons/Hour

Advance Rate (ft/day)	Tunnel Diameter			
	10 feet (210 lb/ft)	20 feet (280 lb/ft)	30 feet (360 lb/ft)	40 feet (430 lb/ft)
300	1.3	1.7	2.3	2.7
500	2.2	2.9	3.8	4.5
750	3.3	4.4	5.6	6.7
1,500	6.5	8.8	11.2	13.5

Conveyor

The items required for extension of a conveyor system include the belt, trough idlers, return idlers, vertical supports, top and bottom stringers, and lateral ties at the top and bottom. The order of magnitude material rates in Table 9-6 are based on an assumed elevation of approximately five feet for the troughed belt.

The pounds of support material per foot of tunnel vary with the advance rate and the tunnel diameter since the belt width and supporting structure are determined by the quantity rate of muck flow. The quantity of support material is less than that required for an equivalent siderail system since the payload is more uniformly distributed over the length of the tunnel, thus reducing the point loading on the structure.

Hydraulic Pipeline

The major contributor to the material rate for the extension of a hydraulic pipeline system is the weight of the pipe. In extremely long horizontal runs a booster pump might be required, but its contribution to the pounds of material per foot of tunnel would be relatively small. Table 9-7 presents order of magnitude data for a double-run pipe system with an allowance of 25 percent of the pipe weight for support materials, fittings, and valves. The horizontal pipe system is isolated from the vertical system to reduce the static pressure on the horizontal pipe, thus reducing the

TABLE 9-6

CONVEYOR EXTENSION
Material Rate, Tons/Hour

Advance Rate (ft/day)	Tunnel Diameter			
	10 feet (25 to 68 lb/ft)	20 feet (60 to 132 lb/ft)	30 feet (82 to 220 lb/ft)	40 feet (120 to 280 lb/ft)
300	0.16	0.37	0.51	0.75
500	0.42	0.78	1.2	1.7
750	0.81	1.4	2.3	3.3
1,500	2.1	4.1	6.9	8.7

TABLE 9-7

HYDRAULIC PIPELINE EXTENSION
Material Rate, Tons/Hour

Advance Rate (ft/day)	Tunnel Diameter			
	10 feet (14 to 38 lb/ft)	20 feet (30 to 83 lb/ft)	30 feet (50 to 147 lb/ft)	40 feet (75 to 200 lb/ft)
300	0.09	0.19	0.31	0.47
500	0.21	0.44	0.78	1.1
750	0.43	0.86	1.5	2.1
1,500	1.2	2.6	4.6	6.2

wall thickness required. The pounds of material per foot of tunnel vary with the advance rate and tunnel diameter since the pipe diameter is a function of the muck flow rate.

Pneumatic Pipeline

Material rates for the extension of a pneumatic pipeline system are presented in Table 9-8. Although it might be expected that the material required for a pneumatic system would be less than for a hydraulic system, the larger pipe diameter and the fact that booster pump and hopper units are required at 1,000-foot intervals more than offset the advantage of a single pipe system. The pounds of material per foot of tunnel vary with advance rate and tunnel diameter as in the case of the hydraulic system.

SERVICE LINE EXTENSION

Order of magnitude estimates of the weight per foot of tunnel length for the support service systems discussed in Chapter 11 are given in Table 9-9. The data for the combined quantities of all service lines are converted to material flow rates for various tunnel diameters and face advance rates in Table 9-10.

The ventilation line is assumed to vary from 18 to 48 inches in diameter, depending on the tunnel diameter and depth. Weight allowances were made for booster blowers at approximately one-half mile intervals and for structural supports. The weights for the ground water removal lines which vary from 14 to 24 inches in diameter include pipe, supports, and pumps.

The electrical service lines include high voltage transmission cable, low voltage distribution, transformers at one-half mile intervals, and supporting brackets.

TABLE 9-8

PNEUMATIC PIPELINE EXTENSION
Material Rate, Tons/Hour

Advance Rate (ft/day)	Tunnel Diameter			
	10 feet (19 to 77 lb/ft)	20 feet (63 to 210 lb/ft)	30 feet (131 to 330 lb/ft)	40 feet (190 to 450 lb/ft)
300	0.12	0.39	0.82	1.2
500	0.30	1.0	1.9	2.5
750	0.64	2.2	3.5	4.8
1,500	2.4	6.6	10.3	14.1

TABLE 9-9

SERVICE LINE WEIGHTS
Pounds per Foot of Tunnel Length

Item	Tunnel Diameter, Feet			
	10	20	30	40
Ventilation	70	115	200	350
Compressed Air	15	25	35	45
Service Water	15	25	35	45
Ground Water	70	90	120	145
Power and Light	15	20	25	30
Total	185	275	415	615

TABLE 9-10

SERVICE LINE EXTENSION
Material Rate, Tons/Hour

Advance Rate (ft/day)	Tunnel Diameter			
	10 feet (185 lb/ft)	20 feet (275 lb/ft)	30 feet (415 lb/ft)	40 feet (615 lb/ft)
300	1.2	1.7	2.6	3.9
500	1.9	2.9	4.3	6.4
750	2.9	4.8	6.5	9.6
1,500	5.7	8.6	12.9	19.2

CHAPTER 10

PERSONNEL

The manning requirements for a tunneling project are dependent on the type of tunneling operations, size and advance rate of the tunnel, and environmental and geological conditions. Each operation is composed of tasks which are performed by men, with the appropriate labor skills, grouped into crews. Only those crews which must be transported within the tunnel complex impose a requirement on the material handling system.

To derive typical tunnel crew requirements, a section of a tunnel project is used. This section consists of a shaft leading to a tunnel which is being driven with one heading. The tunnel is assumed to be about 5 miles long. The total number of men on this portion of the project can be expressed as follows:

$$T_m = M_{ex} + M_{gs} + M_{mh} + M_{ps}$$

where

T_m = total number of men in the tunnel crew

M_{ex} = men required for excavation

M_{gs} = men required for ground support

M_{mh} = men required for material handling

M_{ps} = in-tunnel men required for project support.

The number of men required for each operation is highly dependent on the specific techniques and equipment used for the operation. It is apparent that there are as many values for T_m as there are ways of combining the different possible techniques for each of the operations. Personnel requirements for each of the operations are generated by selecting a technique for each of the operations and then estimating the number of men required for that technique.

It is important to recognize that the personnel requirements are based on extrapolations of current technology and, therefore, involve considerable judgment in manloading the operations. Varying degrees of automation were assumed in order to develop crew sizes that seemed reasonable. In all cases, the manning requirements developed in this chapter are based on the estimated number of tasks involved and the corresponding number of men required to perform these tasks. In Appendix 3A manpower costs are based primarily on functional relationships; that is, crew costs expressed as mathematical functions of tunnel size and advance rate. There is some variance between the crew sizes derived from functional relationships and those developed from conceptual work performance. In general, the functional crew sizes tend to be larger than the crew sizes developed here. This can be attributed to the varying degrees of automation assumed. The order-of-magnitude crew sizes obtained are adequate to determine the quantity of personnel which must be accommodated by the material transport system.

EXCAVATION

For mechanical excavation, the crew is comprised of operating engineers and oilers. Estimated crew sizes are shown in Table 10-1a as a function of advance rate and tunnel diameter.

For conventional or cyclic excavation, the crew is composed of miners, helpers, powder men, nippers, and mucking machine operators. Estimated crew sizes are shown Table 10-1b.

Because of the limited advance rate of the current conventional method of excavation, it is assumed that an automated system is used. The jumbo drills all holes, simultaneously packs them with explosives leaving only the leads to connect, and retreats to a safe distance. Powder men connect the leads and fire the round. Mucking is then performed by some type of high-speed, continuous-operating equipment.

GROUND SUPPORT

The ground support operation is composed of two major tasks: primary support and secondary support. Four basic primary support techniques are considered: rock bolts, shotcrete, steel ribs with lagging, and precast concrete liners. Only one method of applying the secondary concrete liners is considered. The estimated manpower requirements are shown in Table 10-2.

Rock Bolts

The emplacement of rock bolts involves two operations: drilling of the hole and insertion and tightening of the rock bolt assembly. For the advance rates and tunnel sizes considered, it is assumed that the drilling is done by miners who operate banks of pneumatic drills mounted on the rear of the jumbo for cyclic excavation or on platforms in the case of

TABLE 10-1

EXCAVATION CREW SIZES

a. MECHANICAL EXCAVATION

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	2	3	4	5
500	2	3	4	5
750	2	3	5	6
1,500	2	3	5	6

b. CONVENTIONAL EXCAVATION

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	12	14	16	20
500	14	16	18	22
750	16	20	22	26
1,500	20	24	24	32

TABLE 10-2

GROUND SUPPORT MANPOWER REQUIREMENTS

a. ROCK BOLT

Advance Rate (Feet/Day)	Tunnel Diameter (feet)			
	10	20	30	40
300	4	5	6	6
500	4	5	6	6
750	6	6	8	8
1,500	8	8	10	10

b. SHOTCRETE

Advance Rate (Feet/Day)	Tunnel Diameter (feet)			
	10	20	30	40
300	2	2	3	4
500	3	3	4	4
750	4	4	6	6
1,500	5	5	8	8

c. RIBS/LAGGING

Advance Rate (Feet/Day)	Tunnel Diameter (feet)			
	10	20	30	40
300	4	5	6	6
500	5	6	8	8
750	6	6	8	8
1,500	8	8	10	10

d. LINERS

Advance Rate (Feet/Day)	Tunnel Diameter (feet)			
	10	20	30	40
300	5	5	7	7
500	6	6	7	7
750	6	6	8	8
1,500	8	8	10	10

mechanical excavation. After the holes are drilled, the rock bolts are rammed into place, and automatic torque wrenches are used to tighten up the rock bolt assembly. The estimated number of men required is shown in Table 10-2a.

Shotcrete

For the application of shotcrete, one or more pneumatic placer men and helpers stand on the jumbo or on platforms. On the working floor, a compressor man or mixture operator tends the shotcrete equipment. The estimated number of men required is shown in Table 10-2b.

Ribs/Lagging

To emplace the number and size of ribs required for the conditions in this study, it is assumed that some type of positioning and placement equipment such as a hydraulic erector arm, is mounted on the rear of the excavation equipment. The crew would consist of operating engineers, oilers, and miners. The tunnelers would assist rib grappling, ungrappling, position, and alignment and would attach the ribs to the existing ground support by bolting or welding. In addition, they would install the necessary blocking and lagging. The estimated crew requirements are shown in Table 10-2c.

Precast Concrete Lining

The liner segments weigh up to 6.6 tons each; and therefore, special equipment is required for removal from the material handling system, movement to the emplacement area, and positioning for emplacement. The concept envisioned for the development of the crew requirements is based on an overhead monorail system for pickup and movement to the emplacement area. There the units are transferred to hydraulic erector arms for positioning, alignment, and emplacement. Since continuous lining is normally used in difficult ground, this operation must be performed as close to the excavation face as possible. The estimated crew requirements are shown in Table 10-2d.

MATERIAL TRANSPORT

To derive the crew requirements for the material handling systems, the muck-removal and construction-material handling systems were separated into horizontal and vertical transport. The horizontal transport was further subdivided into the extension activities taking place in the near-face zone and the material handling operation and maintenance activities taking place along the entire horizontal transit distance. Several different types of muck removal systems were considered and were, in most cases, combined with a locomotive drive system for the transport of incoming construction materials. The exceptions were the truck system and conventional rail systems which transport material in both directions.

The systems considered are shown in Table 10-3. The estimated crew requirements for these systems are summarized in Table 10-4, where the personnel requirements for the muck-removal and construction-materials systems have been combined. The basis for these estimates are discussed in the following paragraphs.

a. Conveyor

Extension of the locomotive drive system includes laying a rail bed, ties, rail, and accessories. Extension of the conveyor system includes the installation of conveyor brackets, emplacement of conveyor segments, attachment, belt installation, and start-up.

For the operating and maintenance crew, the locomotive drive rail system requires locomotive operators, brakemen, switchmen, and maintenance crew. The conveyor system requires tenders and a maintenance crew based on a factor of 2-1/2 men per mile.

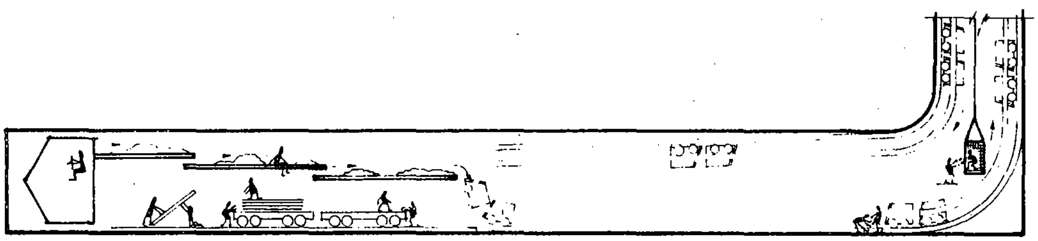


TABLE 10-3

MATERIAL TRANSPORT SYSTEMS

Muck Out	Construction Materials In
Continuous	
a. Conveyor	Locomotive Drive
b. Hydraulic	Locomotive Drive
c. Pneumatic	Locomotive Drive
Unitized	
d. Monorail	Locomotive Drive
e. Siderail	Locomotive Drive
f. Side-Wheel Drive	Side-Wheel Drive
g. Locomotive Drive	Locomotive Drive
h. Truck	Truck

System	Advance Rate (ft/day)	Extension Crew 10	Extension Crew 20	Extension Crew 30	Extension Crew 40	Operating and Maintenance Crew 10	Operating and Maintenance Crew 20	Operating and Maintenance Crew 30	Operating and Maintenance Crew 40	Total Material Handling Crew 10	Total Material Handling Crew 20	Total Material Handling Crew 30	Total Material Handling Crew 40
		Tunnel Diameter (feet)				Tunnel Diameter (feet)				Tunnel Diameter (feet)			
a. CONVEYOR	300	4	8	9	10	9	9	10	10	13	17	19	20
	500	4	8	9	12	9	[illegible]	11	12	13	17	20	24
	750	4	12	12	14	9	10	12	13	13	22	24	27
	1500	5	14	12	14	10	11	13	14	15	25	25	28
b. HYDRAULIC	300	4	7	9	10	5	6	6	7	9	13	15	17
	500	4	7	9	12	5	6	6	8	9	13	15	20
	750	5	10	12	13	5	7	7	10	10	17	19	23
	1500	8	13	13	14	5	8	9	10	13	21	22	24
c. PNEUMATIC	300	4	5	7	7	9	12	16	21	13	17	23	28
	500	4	5	7	7	10	14	17	24	14	19	24	31
	750	5	7	8	9	10	19	23	30	15	26	31	39
	1500	5	9	9	10	15	23	25	33	20	32	34	43
d. MONORAIL e. OR SIDERAIL	300	10	14	22	22	15	15	24	29	25	29	46	51
	500	10	14	22	22	15	15	24	29	25	29	46	51
	750	14	18	26	26	15	15	25	31	29	33	51	57
	1500	14	18	26	26	15	15	25	31	29	33	51	57
f. SIDE-WHEEL DRIVE	300	6	8	12	12	10	10	11	13	[illegible]	18	23	25
	500	6	8	12	12	10	10	11	13	16	18	23	25
	750	9	11	15	15	10	10	11	13	19	21	26	28
	1500	10	12	16	16	10	10	11	13	20	22	27	29
g. LOCOMOTIVE DRIVE	300	4	6	10	10	12	12	16	21	16	18	26	31
	500	4	6	10	10	12	12	16	21	16	18	26	31
	750	6	8	12	12	16	16	21	26	22	24	33	36
	1500	6	8	12	12	22	22	27	29	28	30	39	41
h. TRUCKS	300		2	3	4		17	20	16		19	23	20
	500		2	3	4		25	29	25		27	32	29
	750		3	4	6		37	45	35		40	49	41
	1500		4	5	8		72	89	64		76	94	72

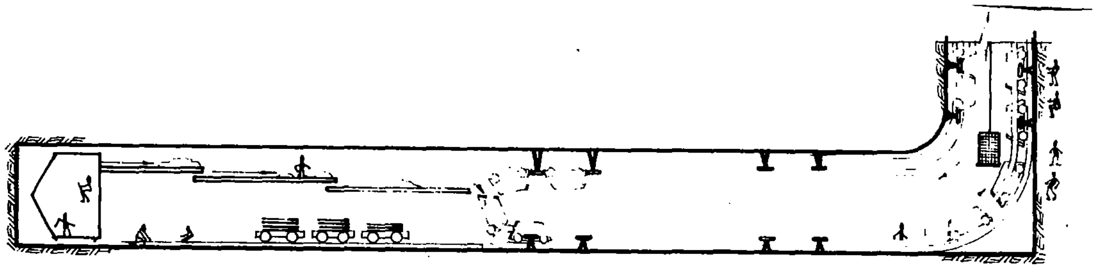
TABLE 10-4

MATERIAL HANDLING CREWS
(Includes Muck and Construction Material Handling Systems)

b. Hydraulic

To extend the hydraulic system, it is assumed that mixing, pumping, and crushing equipment is "leapfrogged" for each increment of pipe advance. Pipe bracketry is attached to the primary support, and inflow and outflow pipes are installed. The normal complement of system extension crews for the locomotive drive system lay the rail bed and install ties, rail, and accessories.

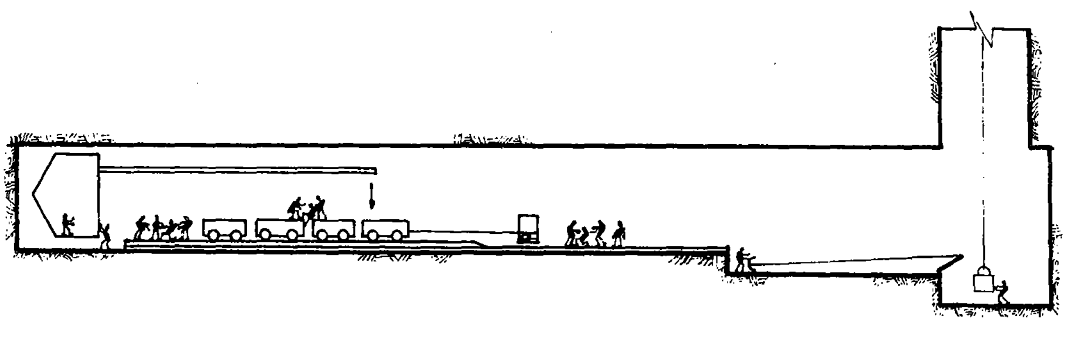
For operating and maintenance, tenders are required for the operating, mixing, pumping, and crushing equipment. Locomotive operators, switchmen, brakemen, and rail maintenance men are required for the rail system.



c. Pneumatic

A pneumatic system is visualized to operate in stages of 1,000 feet each. At the end of each stage, the material will feed into the loading system of the succeeding stage. Personnel for operation should be a minimum if the system is properly instrumented and controlled. Maintenance is expected to be high, requiring a number of men on pipeline repairs; and it may be necessary to run two systems in parallel in order to ensure continuous operation.

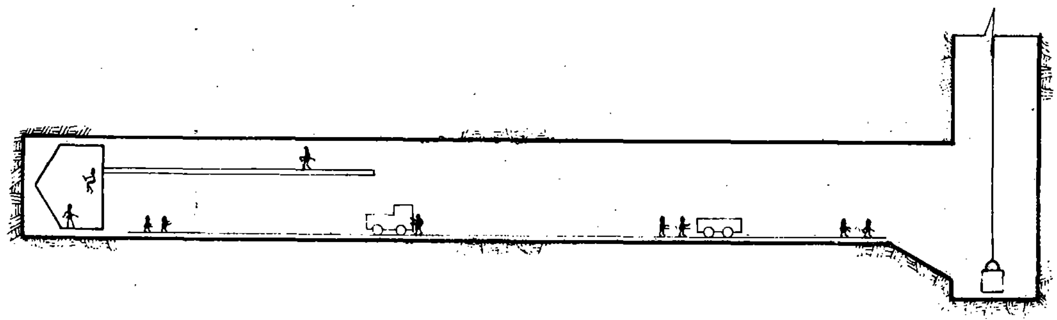
At the transition point from horizontal to vertical, it will be necessary to have two to three operators present as this will be the logical position for both the horizontal and vertical system control panels.



d. e. Monorail or Siderail

The structural support for monorail and siderail systems requires approximately the same amount of effort for installation. For a specified capacity, both systems would require equal automation and operating crews would be about equal. To extend the material handling system, construction for both the muck system and the construction material system is required. A double-track sliding floor is assumed which drops ties and rails as it advances. The siderail or monorail system is extended in much the same way as a standard railroad except that the components and bracketry would be installed in place of ties and rails.

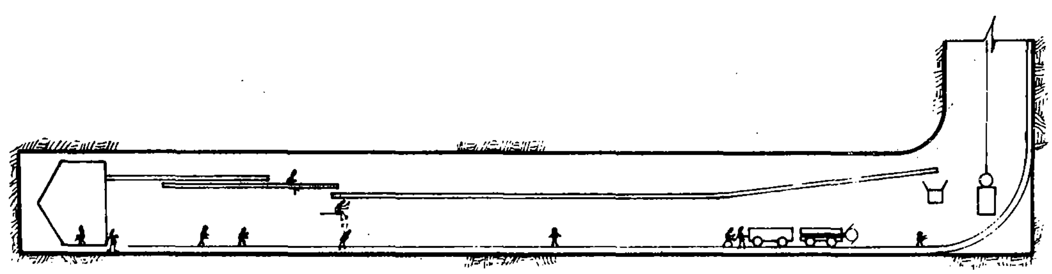
The operating crew of the locomotive drive system includes an operating engineer, a brakeman, and a switchman.



f. Side-Wheel Drive

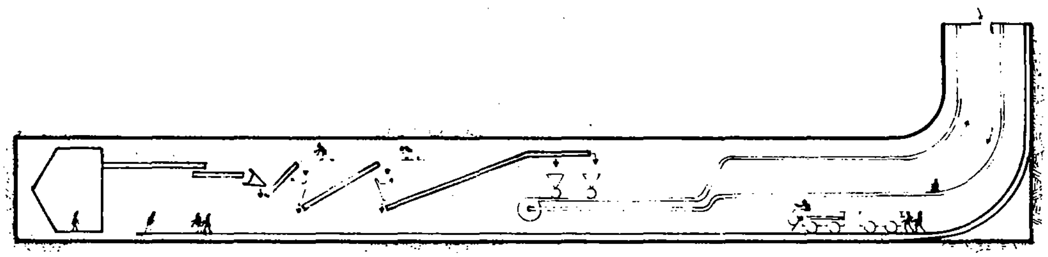
The extension of the side-wheel drive system involves installation of rail bed, laying track of about 24-inch gauge, and emplacing pedestal-mounted drive wheels and electrical motors at appropriate points.

To operate and maintain the material handling system would involve switchmen, control station operators, and track maintenance crews.



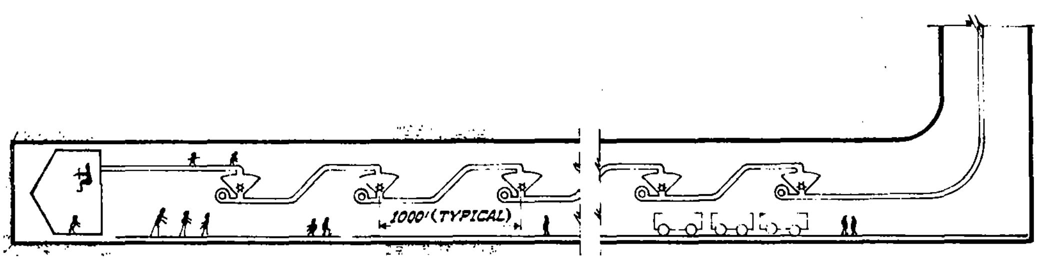
g. Locomotive Drive

The loading system includes an overhead belt conveyor for loading the muck cars and a movable rail deck which follows the excavation and supports the loading conveyor. The trailing edge of the deck ramps down to the permanent rails upon which it rides. The permanent track is laid ahead of the loading deck. Operational and maintenance crews include locomotive operators, conveyor operators, tracklayers, brakemen, switchmen, and track maintenance personnel.



h. Truck

Trucks are assumed to transport both muck and construction materials. It is also assumed that trucks are not used in 10-foot tunnels because of insufficient room. Different sized trucks are assumed to be used for the different sized tunnels. For the 20-foot, 30-foot, and 40-foot tunnels, 5-ton, 20-ton, and 50-ton trucks are used, respectively. The turnaround time in all cases is 20 minutes. To extend the system, a crew is required to lay a level roadbed and apply additives for the formation of a stable surface. A single driver is assigned to each truck. Muck is dumped at the shaft station into a skip pocket, and this operation is overseen by pocket tenders. A crew is required for road maintenance. The smaller crew sizes in the 40-foot tunnel are the result of the use of very large capacity trucks, thus involving fewer truck operators.



PROJECT SUPPORT

The provision of project support involves numerous activities. A ventilation system is required to provide fresh air for the tunnel crew and to maintain adequate temperature and humidity working levels. In addition, bad air and dust must be removed as required. Crews are required to install ventilation pipe and booster fans, as well as maintain the entire ventilation system.

Power must be provided to operate all of the equipment that does not have self-contained power units. Crews must install, operate, and maintain motors, generators, step-down transformers, and compressors.

Crews are required for advancing, mounting, and maintaining lighting systems, high and low pressure water systems, and communication systems. Crews are required for the construction of groundwater sumps and the installation, operation, and maintenance of pumps for water removal. Other manpower requirements include safety inspectors, test personnel, and supervision.

The total manpower requirements for project support are shown in Table 10-5.

TABLE 10-5

PROJECT SUPPORT CREW SIZES

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	9	10	10	12
500	9	10	10	12
750	10	12	12	14
1,500	12	14	14	16

TUNNEL CREW (Total)

The total number of men which must be transported to and from the in-tunnel work stations each work shift is obtained by summing the appropriate excavation, ground support, material transport, and project support crews for a specified advance rate and tunnel diameter. Table 10-6 indicates the range of single-shift, in-tunnel crew sizes for an advance rate of 750 feet per 24-hour day. Other combinations of excavation, ground support, and material transport methods with various advance rates will change the crew sizes by plus or minus 50 percent or more.

TABLE 10-6

TUNNEL CREWS
(Advance Rate = 750 Feet per Day)

Function	Tunnel Diameter (Feet)			
	10	20	30	40
Excavation (Mechanical)	2	3	5	6
Ground Support (Rib/Lag)	6	6	8	8
Material Transport (Locomotive)	22	24	33	36
Project Support	10	12	12	14
Total Crew	40	45	58	64

CHAPTER 11

OTHER MATERIALS AND EQUIPMENT

In addition to muck, ground support materials, materials for systems extension, and personnel, the material transport system must carry other materials and equipment required for excavation, for installation of structural support for apparatus to be installed at a later date, for installation of ground support materials, for ground stabilization, and for other project support functions.

OTHER MATERIALS

Although some of the materials such as ventilation air, compressed air, service water, and ground water are not transported by the material transport system of concern, they are discussed since the quantities required to be handled determine the size of the ducts and pipelines used to transport them. The materials required to extend these ducts and pipelines in pace with the face advance, must be moved to the near face zone by the material transport system.

Excavation

For conventional or cyclic excavation, the materials required include steel or carbide bits for the pneumatic drills, compressed air, service water, and explosives with such accessories as primers, blasting caps, electrical wiring for leads, and detonators. Various hand tools such as spades and picks are needed for working the face after each round to remove loose material. Hand tools are also required for adjusting the drills and various components of a jumbo.

For mechanical excavation, the principal materials are the drag teeth or roller bits on the cutting head. Carbide inserts are usually used in the harder rocks. Rollers consist of a trunnion-mounted conical roller with a series of carbide buttons or teeth on the face of the cone. These cutters must be replaced frequently. The current practice is to retract the cutting head after each 6 feet of advance to inspect the bits for wear and carbide losses.

A typical 14-foot diameter tunnel excavation by conventional methods using 10-foot deep drill holes required about 250 pounds (500 sticks) of dynamite per cycle. This is about 4. 5 pounds per cubic yard excavated. Mayo[1] reports that from 2. 5 to 7 pounds of explosives are required per cubic yard of rock broken, depending on the rock type and tunnel size, with a tendency toward less explosives required per yard broken for the larger size tunnels.

In modern tunnel driving practice, a pattern of blast holes is drilled from a movable drill jumbo which mounts from four to twelve drills. Blast holes are drilled to a depth of 7 to 15 feet and loaded with explosives in order to break the proper amount of muck to balance the particular cycle.

Nitroglycerine explosives have been largely replaced in recent years by ANFO (ammonium nitrate - fuel oil) mixtures which are much cheaper and can be loaded by mechanical means. Liquid blasting slurries and metallic powders are now replacing ANFO in some applications.

The proper explosive strength for a particular application depends on the rock type. Hard brittle rocks are broken by high-velocity explosives, whereas soft rocks respond best to low-velocity explosives. Hole spacing is a function of velocity and rock hardness. A typical hole spacing in medium hard rock would be 1-3/4-inch holes on 2-1/2-foot centers using 3 to 4 pounds of ANFO per cubic yard.

"Powder factors" of ANFO and slurry explosives for tunnel use are normally in the range of 3 to 5 pounds per cubic yard, whereas dynamites may be as much as 7 pounds per cubic yard. The price of ANFO is normally only about one-third of that of nitroglycerine dynamites.

Interface Load Support

Tunnels constructed for the use of high-speed ground transportation vehicles may require a special interior lining for the guidance and support of such vehicles. This imposes additional support requirements that are met by installing interface load supports simultaneously with or immediately after the installation of rock load supports. The interface load is the live load due to the transportation system which must be supported in addition to the rock load. In a study by Harza,[2] based on a postulated high-speed ground transportation system, it was determined that the web depth for the interface load supports is in all cases equal to or less than that for the rock load supports.

Table 11-1 gives the quantity of interface load support per linear foot of tunnel for various tunnel diameters and assumed live loads in pounds per cubic foot. The data for the 10-foot, 20-foot, and 30-foot tunnel diameters were interpolated from Harza data. The 40-foot tunnel data were extrapolated on the basis of the proportional rate of increase with tunnel diameter. Table 11-2 shows the transport requirement range for interface load support materials in tons per hour based on the data from Table 11-1.

TABLE 11-1

INTERFACE LOAD SUPPORT IN TUNNELS
(Pounds per Linear Foot of Tunnel)

Finished Tunnel Diameter	Live Load			
	4 pcf	10 pcf	15 pcf	20 pcf
10 feet	5	13	20	27
20 feet	32	81	122	161
30 feet	107	264	398	540
40 feet	444	704	1,058	1,438

TABLE 11-2

QUANTITIES OF INTERFACE LOAD SUPPORTS
(Tons per Hour)

Advance Rate (feet/day)	Tunnel Diameter (feet)							
	10		20		30		40	
	4 pcf	20 pcf	4 pcf	20 pcf	4 pcf	20 pcf	4 pcf	20 pcf
300	0.031	0.168	0.200	1.00	0.668	3.37	2.78	8.96
500	0.052	0.281	0.333	1.67	1.110	5.61	4.13	14.90
750	0.078	0.421	0.500	2.50	1.67	8.43	6.94	22.20
1,500	0.156	0.842	1.00	5.00	3.35	16.80	13.90	44.90

Support Services

Ventilation - Ventilation is required at all locations where men or equipment are working. State codes and U. S. Bureau of Mines recommendations are used to estimate the quantity of air required.

To provide for the needs of the excavation work crew, fresh air outlets are placed near the face and must advance at the same average rate as the face advance. For normal conditions, 100 cubic feet per minute per man or 50 cubic feet per minute per square foot of face, whichever is larger, is considered adequate. As rock temperatures increase with greater depth, more air or mechanical cooling is required. Harza(2) indicates a fourfold increase in air requirement between 1, 750 and 3, 500 feet of depth, as shown in Figure 11-1. Special provisions to control dust may be needed in some cases. When conventional drill and blast excavation is used, a method of reversing the air flow is usually provided.

Additional air is required when diesel or battery-powered equipment or open electric equipment operates in the tunnel. The State Mine of California Codes has established a standard of 75 cubic feet per minute per brake horsepower in the tunnel at any one time for diesel equipment. Electric or battery equipment requires less ventilation. The U. S. Bureau of Mines requires 150 cubic feet per minute per brake horsepower and allows only engines which have been tested in prototype by their laboratory.

A typical example of a recent 4-mile long tunnel constructed by use of a mechanical mole is the 12-foot diameter River Mountain Tunnel at Henderson, Nevada, which used 18, 000 cubic feet per minute of air supplied through a 30-inch pipe by 40-horsepower fans on 3, 000-foot centers.

In general, fan lines are between 12 and 48 inches in diameter and are made of lightweight metal. The pipe is usually hung from the crown of the tunnel or tunnel support. As the face advances, booster fans and sections of this pipe need to be transported to the working zone for installation.

Compressed Air - Compressed air is required for the operation of pneumatic equipment and other service uses. It is provided from external compressors through high pressure lines (approximately 110 pounds per square inch gauge in 4-inch to 8-inch diameter lines) which may be installed as multiple lines coupled with receivers to handle high air surge. The compressed air line is normally attached to the tunnel wall or ground support structure.

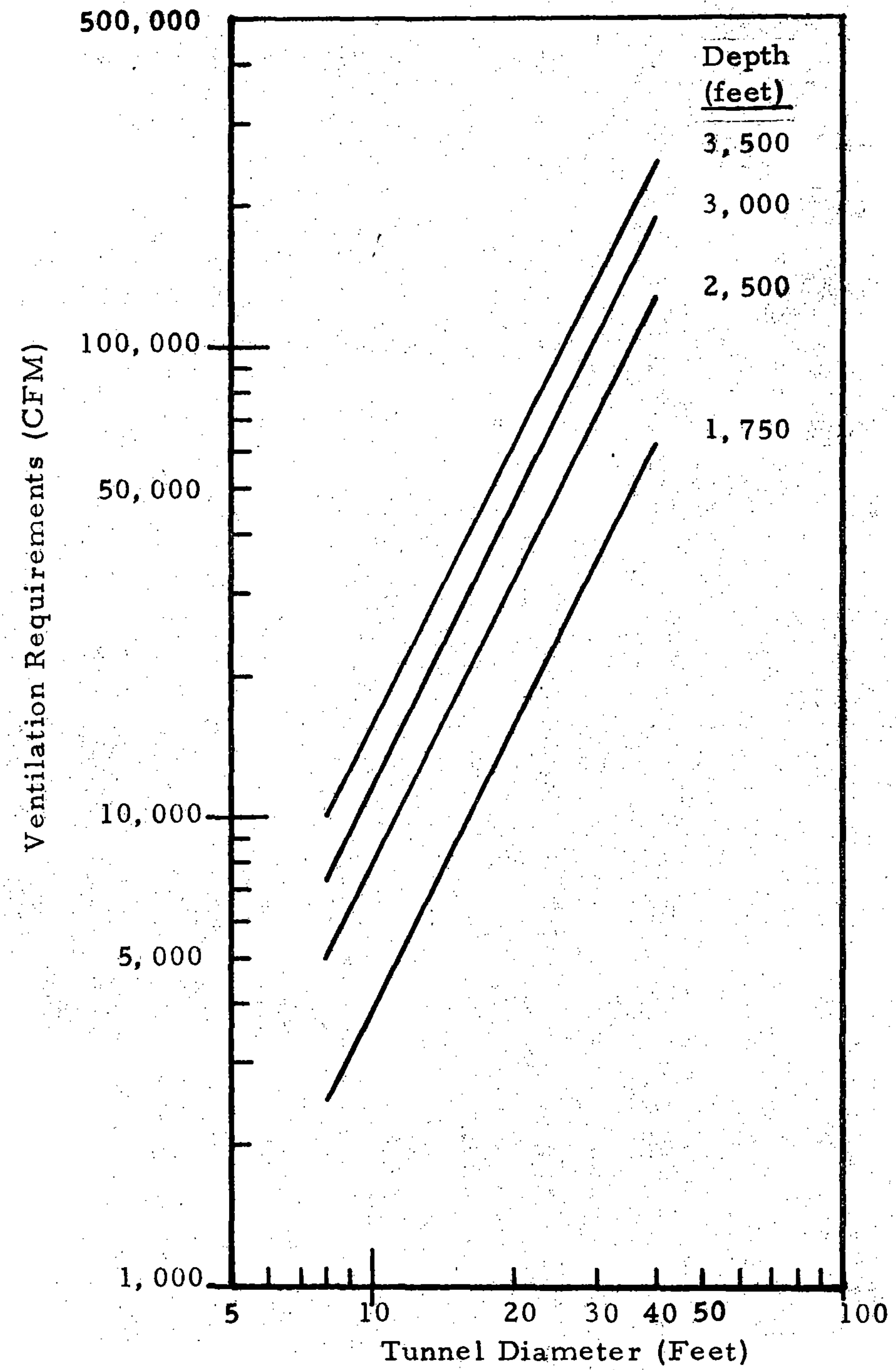


FIGURE 11-1

VENTILATION REQUIREMENTS

After Harza[2]

Service Water - Under some dusting conditions, the face is sprayed with water containing a wetting agent (detergent) to control the dust. The muck pile is also sprayed to control dust during loading. Water also is required for cooling equipment, hydraulic systems, and drilling water if conventional excavation is used. It is usually supplied at about 80 pounds per square inch gauge through a 4- to 6-inch pipeline. This line must be extended from the external water source at the same rate as the face advance.

Groundwater - The flow of groundwater may vary between 1 gallon per minute and 35,000 gallons per minute per mile of tunnel for the various rock groups at depths of 100 to 3,500 feet. The larger rates of flow need to be reduced to permit excavation operations, thus reducing the average requirement for water removal. However, adequate standby capacity must be available to take care of the temporary situation to prevent possible flooding of the tunnel.

It has been estimated by Harza(2) that the leakage rates indicated in Table 11-3 are tolerable. The sustained rates vary with depth due to the cost trade-off between pumping and grouting. It should be realized, however, that there are many cases where grouting or any other known method will not control the water.

The inflow of water is collected in sumps from which it is pumped into a discharge line at several points along the tunnel. The size of the line must be large enough to handle the total cumulative flow anticipated at the end of the tunnel. Booster pumps may be used to reduce the back pressure at the point of entry. Discharge lines for average tunnel operations usually range upwards from 14 inches in diameter. However, for extremely long tunnels larger sizes may be required for insurance against silting. The average advance rate of the discharge line must be the same as that of the tunnel face.

Flows of hot water or corrosive water demand special techniques. For hot water conditions, refrigeration cooling is required to produce an acceptable work zone. Pump lines filled with hot water radiate heat into other remote areas. Insulated pipes are often employed for drains as well as for the cooled and dehumidified ventilation air.

Corrosive water is a special situation of hazard because of the rapid deterioration of steel tunnel sets, concrete, rails and other guideways, and all equipment. If corrosive water is encountered, rubber-lined discharge lines and pumps must be used throughout. Asphalt coatings may be applied to steel sets and liner plates, while every precaution is taken to prevent excessive contact between water and equipment.

TABLE 11-3

TOLERABLE LEAKAGE IN TUNNELS
After Harza(2)

a. TOLERABLE LEAKAGE IN TUNNELS FOR MOST GROUND TYPES
(Gallons Per Minute Per Mile)

	Depth (Feet)				
	100	500	1000	2000	3500
Initial	3000	3000	3000	3000	3000
Sustained	1500	250	110	50	25

b. TOLERABLE LEAKAGE IN TUNNELS WITH FLOWING GROUND
(Gallons Per Minute Per Zone)

	Zone Width 300 ft, Depth 100 ft	Zone Width 225 ft, Depth 500 ft	Zone Width 150 ft, Depth 1000 ft	Zone Width 100 ft, Depth 2000 ft	Zone Width 100 ft, Depth 3500 ft
Initial	600	600	600	600	600
Sustained	300	60	30	15	8.5

Lighting and Power - Light is generally provided in the tunnel by a 120-volt, two-wire system with bare lamps attached at approximately 25-foot intervals. The wire is supported from the side of the tunnel by temporary supports. This requires about 200 bulbs per mile which must be replaced at the end of their useful life. About 52 kilowatts per mile are required to provide adequate light over the length of the tunnel. In the working zone, the intensity is usually higher. Portable floodlights give adequate illumination. Minimum illumination is generally controlled by State tunnel codes.

In addition to the requirement for light in the tunnel and the working zone, electric power is often required at the working face and along the tunnel for the operation of construction equipment, pumps, and fans. Power is transmitted through the tunnel at high voltage (frequently 4,160 volts) and stepped down (480/240/120) at periodic intervals for light and at the point of need for other uses. Therefore, transmission lines, wires for lighting, and transformers must be transported to the working zone and installed at the same average rate as the face advance.

EQUIPMENT

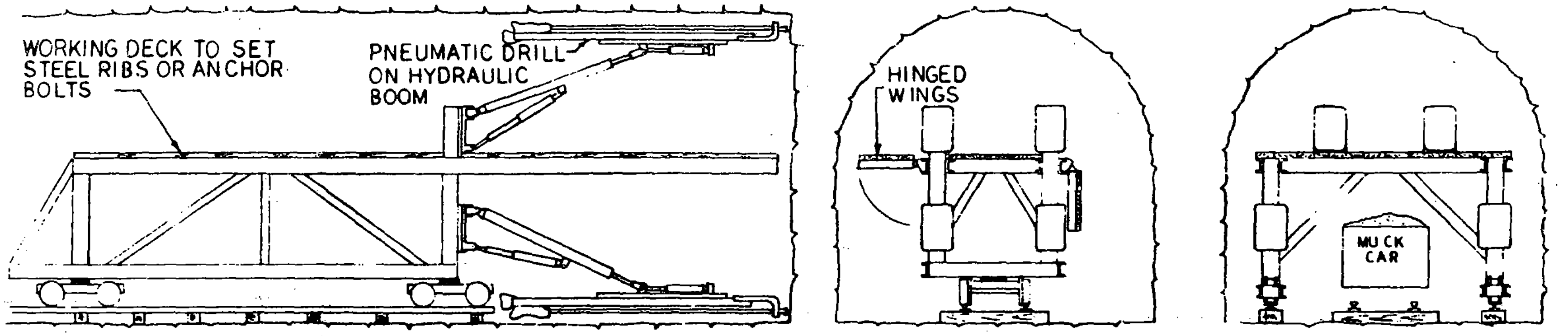
Although the major equipment used for excavation and ground support installation normally stays in the face and near-face zones and advances with the heading, situations may occur which require the removal and replacement of major components of this equipment. A means of transporting these components must be provided. Ground stabilization equipment and other project support equipment which may be needed only intermittently must be transported to and from the face zone, near-face zone and other points on an as-needed basis. Maintenance parts and supplies must also be transported to the location of this equipment.

Excavation Equipment

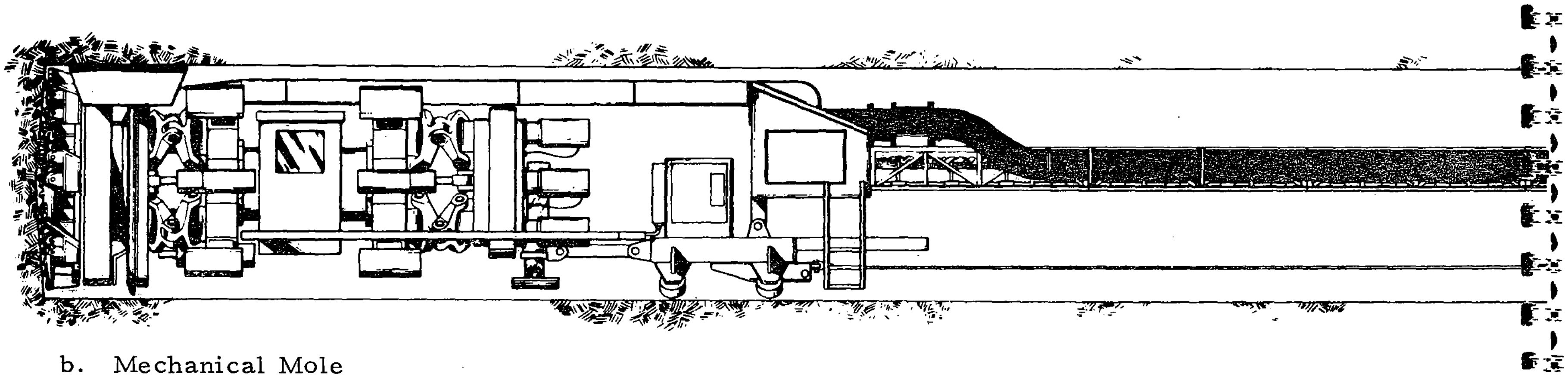
In general, there are two common methods of excavating in-situ material from the tunnel face: conventional cyclic and mechanical excavation. Both methods involve the use of large, mobile equipment which occupies much or all of the space at the face zone. Typical equipment of each type is shown in Figure 11-2.

For conventional excavation, a drill jumbo and mucking machine are used. The drill jumbo is a mobile work platform upon which pneumatic drills are mounted. The drills are attached to movable hydraulic arms which are controlled by a miner who stands on the deck of the jumbo. After drilling the blast holes in a designated pattern, the rig is moved back from the face for the blasting operation. Mucking machines then move forward and remove the blasted rock from the face zone. In small tunnels, mucking usually is done by a small, air-operated, over-shot shovel that runs on the same track as the muck cars. For medium-sized tunnels, 12 feet to 20 feet in diameter, an electrically operated machine scoops up the muck and places it on a short conveyor belt that feeds back to a loading point. For larger tunnels, a diesel powered shovel is usually used or some type of front-end or side discharging loader mounted on a tractor.

For mechanical excavation, various types of moles are used. Typically, moles are cylindrical in shape and consist of an electric motor drive, cutting head, control panel, thrust jacks, tailskin, and muck conveyor. In some cases, the main power plant activating the cutting head is remote from the unit and is positioned to the rear of the shell. However, the motors may be multiple mounted in the unit with direct drive of the cutter head or heads. Currently in the United States the cutter head is circular and produces a relatively smooth circular bore. Muck is loaded through the mole to the rear of the operation. The shell diameter is slightly less than the cutter head diameter.



a. Drill Jumbo



b. Mechanical Mole

FIGURE 11-2

EXCAVATION EQUIPMENT

For soft or difficult ground, the shield technique of tunneling is used. The shield, which provides crown support during excavation, is a cylindrically shaped unit constructed of heavy steel plates. At the loading end of the shield is a cutting edge and hood while at the rear is the tail-skin. To advance, hydraulic jacks located inside the shield at the rear thrust against the completed primary lining pushing the shield forward. Tunnel alignment is accomplished by activating individual or separate banks of jacks. Excavation is performed by mechanical moles operating within the shield. Rotary bit moles are used in medium to hard rock. Drag bit mole types are used in soft ground except for the most difficult of soft ground conditions when hand excavation is required.

Ground Support Equipment

The ground support operation can be divided into two separate phases, provision of primary and installation of secondary lining. Currently, there are four basic methods of primary support: rock bolts, shotcrete, ribs, and liners. For secondary support, concrete is usually used and is poured with or without reinforcing steel. Steel or cast iron liners also are sometimes used. The equipment involved for emplacement is often specially designed to suit each job.

Rock Bolt Installation - The installation of rock bolts involves the use of pneumatic drills suitable for drilling the required rock bolt diameter and length. Rock bolts are inserted in the holes and rammed home. Nuts are then tightened onto a holding plate to complete the installation. A driving tool is used to drive the bolt home, and an impact torque wrench is used to tighten the assembly. The pneumatic drills and driving tools can be multiple mounted on mobile jumbos for simultaneously installing bolts. Sometimes the drilling and driving capabilities are combined on the same units. While there are different types of rock bolts requiring somewhat different procedures, the overall type of equipment involved tends to remain the same with the exception of rock bolts which have grout inserted into the hole. For this type, a pneumatic grouter is required in addition to the other equipment.

Shotcrete and Gunite Application - These machines involve the mixing of mortar or concrete, which is then conveyed through a hose and pneumatically projected at high velocity onto a surface. There are two basic shotcreting processes: dry mix and wet mix.

In the dry mix process, cement and damp sand are mixed. This mixture is fed into a special mechanical feeder or gun. The mixture is then metered into a delivery hose by a feed wheel or distributor. Compressed air carries the mixture through the delivery hose to a special nozzle where water is introduced under pressure. The total mixture is then jetted from the nozzle at high velocity onto the surface to be shotcreted.

In the wet mix process, all of the ingredients including water are combined in a mixing machine. The mixture is introduced into the chamber of the delivery equipment where it is metered into a delivery hose and conveyed by compressed air or other means to a nozzle. Additional air is injected at the nozzle to increase the velocity of the mixture for application. The wet-mix shotcrete machines consist of a premixer where the water, aggregate, and cement are mixed in a conventional type concrete mixer and then fed by means of a pump through a hose to the nozzle where air at 150 to 175 pounds per square inch is injected into the nozzle propelling the material to the surface being shotcreted.

The gunite machine consists of a pot or bin which receives the mixture of dry sand and cement. The mixture is fed by gravity through a series of air locks into a pressure chamber under 100 to 150 pounds of air pressure; then the dry mixture passes through a hose to the nozzle, where a metered quantity of water is added to the stream of sand and cement as it is blown from the nozzle. Mixing takes place at the nozzle and in transit as the material strikes the surface being gunited. The dry mix shotcrete machines operate in very much the same way as the gunite machines, but use a larger aggregate such as number 4 pea gravel.

Rib and Liner Installation - Erectors and applicators for rib and liner installation can either be installed on a boring machine or on the drill jumbo, or they may be installed on their own transport unit. They serve the function of raising the liners, ribs, or steel to the back of the tunnel, manipulating them for positioning against the ground and holding the units while being bolted or welded. To date, there has been no standardization in the design of equipment used to accomplish this; therefore, emplacement equipment is peculiar to each tunnel project. The rib or liner units generally are picked up in the near-face zone by an overhead monorail system and hoisted to the crown of the tunnel. The units are then moved to a point just behind the excavation operation. There they are transferred to a hydraulic erector arm which is attached to the rear end of the excavation equipment. Most erectors, at present, are operated hydraulically and normally consist of a large arm which can be moved in a complete circle around the center pivot point of either the mole or of the carriage on which they are installed. They are massive in structure and possess the capability of picking up a structural unit from either a transporting car or from an overhead monorail hoist. Under full-time control of the operator, they position the structural member by means of extensible hydraulically operated arms in the same manner that a man would pick up a small steel plate and hold it in position until a helper could either bolt it in the position required or weld it to other structural items. The emplacement is completed when the units have been bolted or welded to the existing structure.

Secondary linings are usually constructed of concrete and require specialized equipment for forming, mixing, hauling, and placing. Tunnel forms are built of steel and are either nontelescopic or telescopic. Nontelescopic forms are used on short tunnels. Telescopic forms are used on long tunnels and are designed so that they can be collapsed to pass through forms already in place. The form is set up in front of the other forms ready to receive more concrete. The units are usually 20 or 25 feet long. In some cases, the slip-form principle also has been used. Concrete is placed behind the steel forms with either a pump or pneumatic placer, as illustrated in Figure 11-3. Concrete pumps are electrically powered and mounted on a flat car that runs on the muck track. A conveyor is used to elevate the concrete to feed into a hopper. An entire unit consists of a conveyor, concrete pump, and tower car all assembled into one train so that as the form is filled, the entire unit is moved backward to withdraw the slick pipe. The range of current pump capacities are from 15 to 65 cubic yards per hour.

In another method, compressed air is used to blow the concrete from the placer to the form. For most tunnel jobs, an air receiver is mounted on a flat car that travels with the pneumatic gun carriage as the form is filled. The rail-mounted gun depicted in Figure 11-3B is shown being loaded by an agitator car which has been elevated slightly for direct feeding into the gun. In all cases, the concrete is vibrated to eliminate voids and increase density.

For short tunnels, 2- to 4-cubic-yard hopper cars may be used to bring the concrete to the placer. Concrete can also be hydraulically transported in pipelines for several thousand feet as has been done at the Nevada Test Site of the U. S. Atomic Energy Commission by use of modified "mud" pumps as developed for the large hole drilling industry. In longer tunnels, agitator cars are used and consist of a standard, electrically or diesel-driven agitator unit mounted on a flat car or truck.

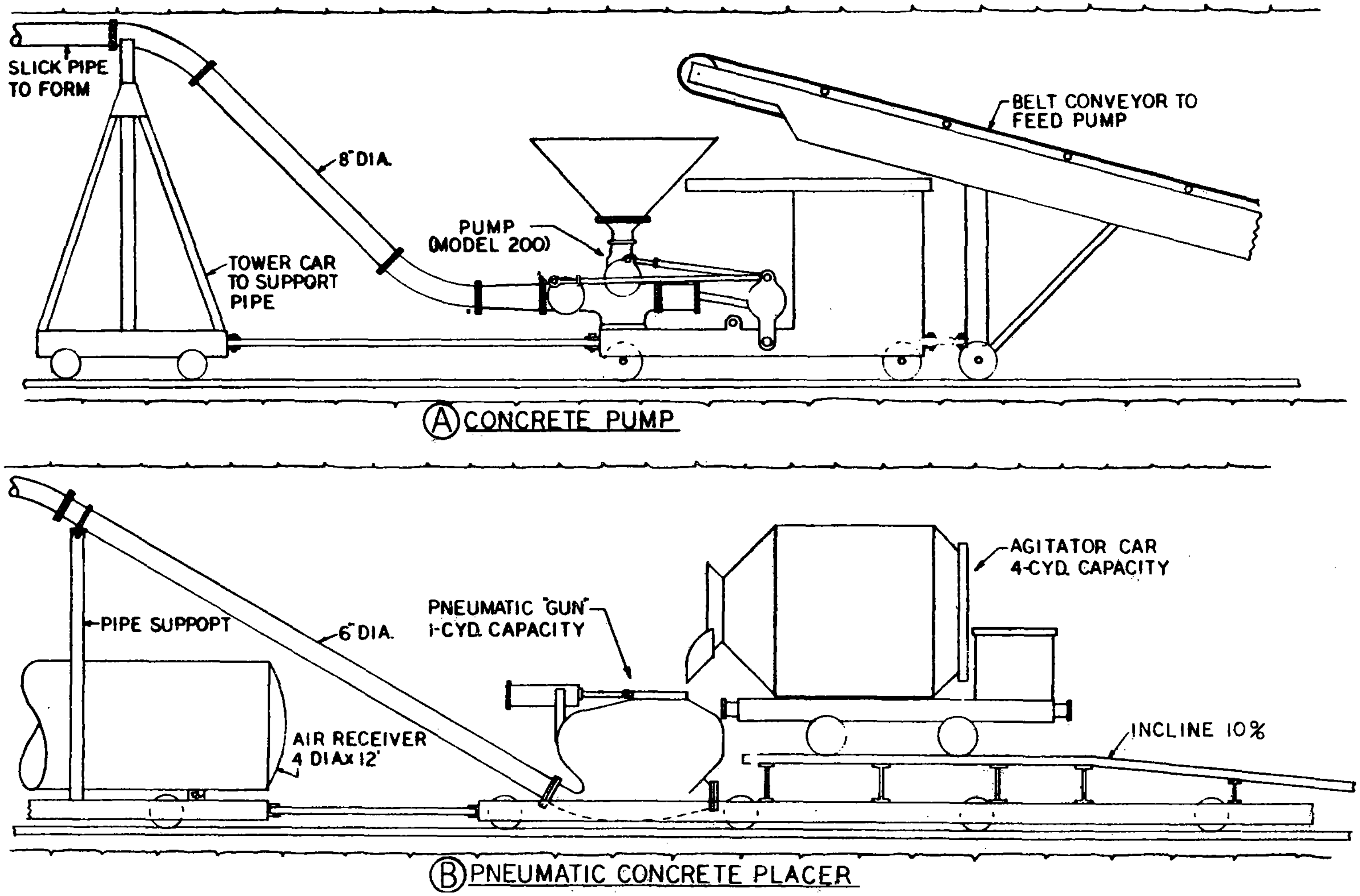


FIGURE 11-3

CONCRETE EMPLACEMENT EQUIPMENT

After Mayo(1)

A mixing machine or plant is required to produce concrete at the needed rate. This equipment is currently set up either outside the tunnel complex or next to the concrete placer.

Ground Stabilization Equipment

Two methods of ground stabilization have been used: grouting and freezing. Grouting applicators are of several designs but fundamentally consist of a high pressure reciprocating pump which forces the slurry of water and cement or numerous other mixes of bentonite, resins, or "muds" into the fractured rock. "Muds," have been developed to a high degree of technology in the petroleum industry and can be of considerable value to the tunneling industry when properly used.

Refrigeration or ground freezing units are usually tailor-made for the job and coupled with a circulating pipe installation designed to give maximum heat transfer from the ground consistent with allowable economies. Such systems are usually very expensive to install and require several months of operation of the refrigeration to properly freeze the running ground.

Project Support Equipment

The provision of project support involves the use of various types of equipment. The ventilation system requires equipment for the intermittent installation of blower fans and the continuous emplacement of ventilation pipe. Dust control equipment may also be required. High and low pressure air and water lines must be continually extended and require advance equipment for temporary bypassing and emplacement of line segments. Step-down transformers must be periodically installed. Equipment and tools are required for the installation of transformers as well as transmission lines and lighting system. Pumps are required for the removal of groundwater. In addition, other equipment needed for various activities include air compressors, electric and diesel motors, circuit breakers, control equipment, and welding equipment.

Maintenance equipment is required to service those items which cannot be brought to the surface for maintenance and repair. This includes lubrication carts, check-out equipment, wrenches, pulleys, hand tools, inspection equipment, and monitoring devices. Diagnostic equipment will become more prevalent as increasing degrees of automation are incorporated into the tunneling process.

Depending on conditions, various emergency equipment is needed such as first aid equipment (e.g., oxygen tanks, decompression chambers), emergency power generators, and excavation equipment for handling cave-ins or accidents.

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2. "High-Speed Ground Transportation Tunnel Design and Cost Data," Harza Engineering Company, PB 178201, March 1968.

PART 3: SYSTEMS ANALYSIS

CHAPTER 12

SYSTEMS ANALYSIS APPROACH

The purpose of the systems analysis performed as an integral part of this study is twofold:

- To evaluate the cost at various performance levels for alternate modes of material transport under conditions typical of those anticipated for tunneling situations.

- To provide a basis for estimating the cost of material handling for future tunneling projects.

The upper limit of face advance rates and continuity of operations assumed for this study are well beyond those achieved by present practice. The analysis was extended into this futuristic range to identify the cost incentive for striving to improve these factors.

The basic approach to the analysis is:

- Construct conceptual models for operational situations and material handling systems which appear reasonable for future tunneling projects.

- Develop mathematical relationships or models to represent the performance characteristics and system cost factors for various material handling systems and operational situations.

- Exercise the analytical models to generate cost/performance data for selected transport modes, transport system costs, and total material handling costs per unit tunnel length for selected integrated material handling systems operating under various situations.

Analytical models are developed at two levels; one to evaluate alternate transport modes performing the transport function only, and the other to evaluate integrated material handling systems which perform all essential material handling functions (transport, loading, intermode transfer, system extension) within the defined system boundaries and under specified operating situations.

The purpose of the integrated system model is to evaluate the alternate transport modes in the "real" environment of a future, high advance rate tunneling project. This requires consideration of cost factors for the entire material handling system during the total life cycle for the system. It also requires that a particular tunneling situation be defined which, in general, will set the performance level required of the material handling system.

The following "life cycle scenario" for a material handling system used in a typical tunneling situation traces the material handling system from development and acquisition (birth) through final salvage or discard (death) for a specific equipment system and specific construction strategy. This case, used for illustration, is only one of the many cases which can be analyzed by the integrated system model.

LIFE CYCLE SCENARIO

The tunnel construction project is for a very long, deep underground tunnel with access through vertical shafts located approximately 20 miles apart.

Strategy

The construction strategy is to divide the total tunnel length into 40-mile units. A separate construction team with a set of equipment is given responsibility for completing each unit of tunnel. The excavation strategy used by the construction team is to begin tunnel excavation at a shaft station, previously prepared by another crew, and work in one direction away from the shaft for 10 miles, then return the equipment to the shaft station and work in the opposite direction from the shaft, thus producing 20 miles of tunnel with a 10-mile long material transport system.

After completion of the initial two 10-mile segments, the crew and equipment are removed from the tunnel and installed in the second shaft station where the sequence is repeated.

Material Handling System

An integrated material handling system is assembled, by selection from the feasible alternate equipment systems and required work crews, to perform all functions essential for transporting all inbound and outbound materials. These functional systems include equipment and crews for:

- Muck removal including loading in the near-face zone, horizontal transport, intermode transfer at the shaft station, vertical lifting through the shaft, and unloading at the surface. It is assumed that on the surface, the value of the muck (as fill or aggregate) equals the cost of disposal, thus eliminating many complications introduced by including a variety of surface transport systems or processes. In this example case, the muck removal system consists of hardware and crews for low pressure hydraulic horizontal transport, slurry transfer from the horizontal to the vertical transport system, vertical transport in a high pressure hydraulic system, muck discharge at the surface, and a continuously moving loading and extension system in the near-face zone, consisting of a sliding floor, short conveyors, crushers, loading hoppers, and pipe extension devices.

- Incoming materials transport including loading at the surface, lowering through the shaft, transfer to the horizontal transport system, and unloading near the face. It is assumed that materials enter the system at the surface properly palletized to meet the demanding requirements of the complicated and closely synchronized operation. The example in this case consists of a hoist for lowering material, a crew and equipment for transferring material from the hoist to a horizontal conventional rail transport system, the horizontal system, and a constantly moving system for unloading material and extending the rails in the near-face zone.

Preexcavation Preparation

Once the configuration of the material handling system has been selected, procurement of the equipment and its preparation for use is begun. This includes:

- Engineering and developing specialized equipment.
- Procuring, component by component, the complete system.
- Procuring an initial inventory of spare parts, components, and supplies to maintain the system.
- Mobilization or assembly of the component equipment at the site.
- Setting up the appropriate equipment in the shaft and in the shaft station.
- Training of operating personnel and shakedown of the equipment for operation in the integrated system.

Tunnel Construction

First Use - During this phase of the system life cycle the construction team provides for:

- Consumption of energy by the system.
- Operation and maintenance including replenishment of spare parts and supplies.
- Extension of the system, including labor and materials, to follow tunnel advance.

Availability - In a realistic tunneling environment, breakdowns of equipment and scheduling problems will delay the project. Careful planning is used to minimize the delays because work crews and equipment are idle during delay periods. For accurate estimates of project material handling cost, predictable delays must be realistically accounted for by some means such as an "availability" factor. Availability factors are introduced to account for "downtime" due to failures within the material handling system and also to account for material handling system downtime due to failures in other systems which, when inoperative, prevent the use of the material handling system.

System Reuse - To obtain economical use of the equipment, it must be reused on successive tunnel segments until it is no longer serviceable. In this example, the material handling equipment is assumed to have a useful life of forty miles of tunnel, which corresponds to the project length.

For the excavation strategy adopted for this sample case, the equipment is used on four successive 10-mile tunnel segments. Each time the material handling system is used on a new segment, the following life cycle elements must be repeated:

- Mobilization including disassembly and moving equipment to the new location. For the specified strategy, every other reuse mobilization involves removing the vertical transport system from the shaft, raising all other units of the material handling system through the shaft, surface transporting to the new shaft, and lowering the tunnel equipment through the shaft to the shaft station.
- Setup or reassembly of the system. For the specified strategy, every other reuse setup includes setup of the vertical transport system in the shaft.
- Shakedown of the reassembled system. For the specified strategy, every other reuse shakedown would not include shakedown of the vertical transport system since it would not be moved to a new location.

Each reuse cycle must provide for:

- Energy consumption by the system.
- Operation and maintenance.

Equipment Disposal

After the equipment has been reused to the limit of its useful life, the material handling system (equipment and crews) of concern is assumed to be disbanded. Many hardware components of the system will be worn out but others may have salvage value. It is assumed that the equipment is sold for salvage or disposed of for other uses. Hence, the salvage value of the equipment is credited to the cost of the material handling system.

LIFE CYCLE COST ELEMENTS

The elements of cost contributing to the total cost of the material handling system are discussed in the life cycle scenario and may be summarized as:

- Engineering and Development - The cost of developing equipment up to the point where an operational capability has been demonstrated.
- Equipment Acquisition - The procurement cost of new equipment.
- Mobilization - The cost of moving equipment to a new location. It may also include disassembly of the equipment where this is required prior to moving.
- Setup - The cost of assembling and checking out equipment after it has been moved.
- Training and Shakedown - The cost of training crews to use the equipment at a new location.
- Initial Spares - The spare parts and spare equipment procured at the beginning of a project.
- Operation - All operating costs including crews, energy, maintenance, and replenishment spares.
- Disposal - The salvage value of equipment at the end of its useful life.

ANALYSIS METHOD

The analytical method used in this study is represented diagrammatically in Figure 12-1 which emphasizes the two levels of evaluation performed.

Preanalysis

The results of activities performed preparatory to the formal analysis using modeling techniques are discussed in Chapters 1 through 11 of the report. These activities include:

- Problem definition
- Data collection
- Identification of parameters
- Definition of approaches to material handling systems
- Definition of muck characteristics and quantities
- Definition of quantities and characteristics of incoming materials
- Development of concepts for improvement of systems
- Establishment of material handling requirements for outbound and incoming materials.

First Phase

The first phase of the analysis, which is discussed in detail in Appendix 3B, consists of:

- Processing and supplementing background data to obtain input data in a form suitable for use in analytical models.
- Development of performance models and cost models for the various transport modes of interest.
- Application of the performance and cost models to generate cost/performance measures (cost per unit performance capability) for each of the transport modes.

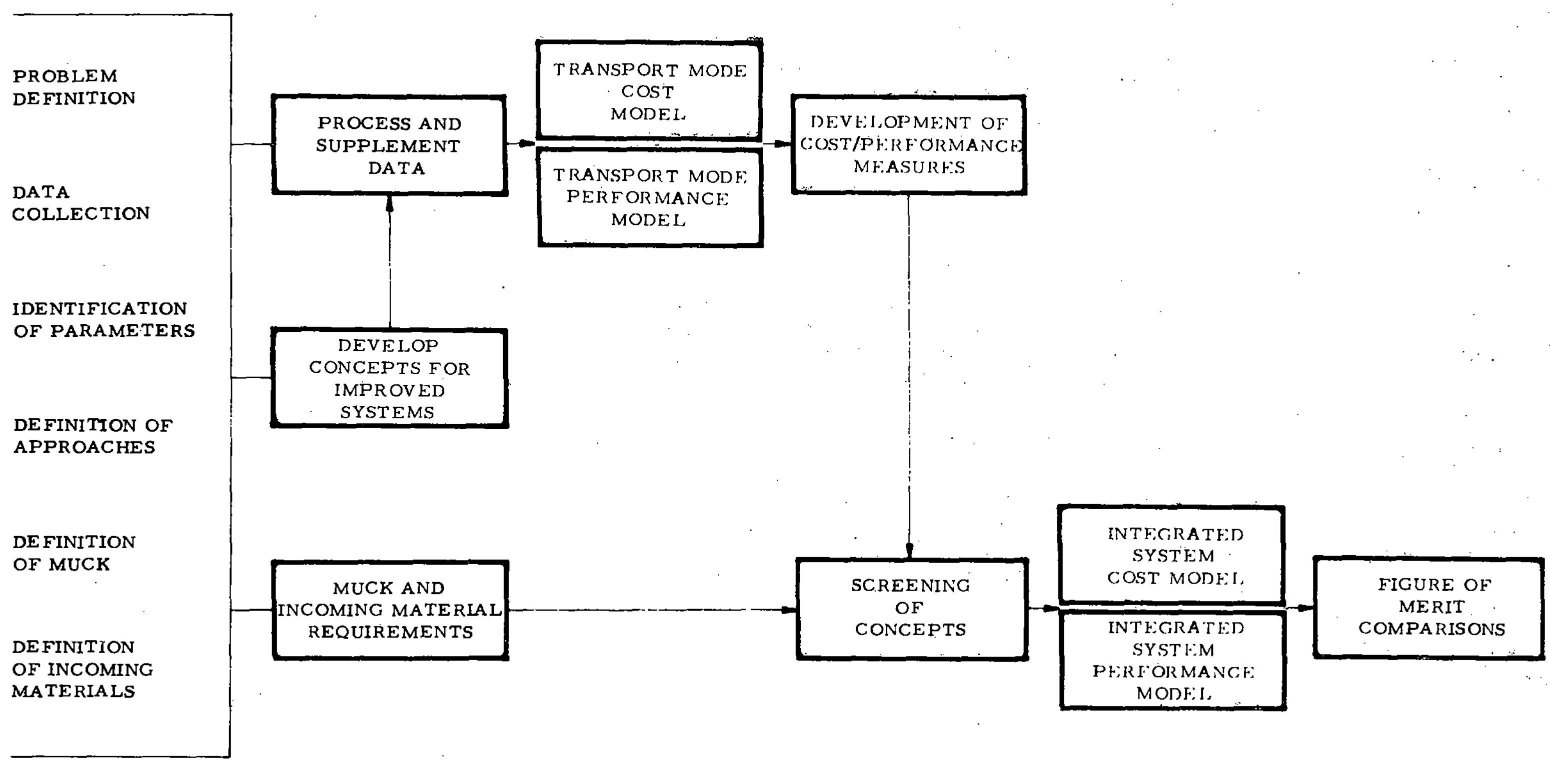

FIGURE 12-1

ANALYSIS FLOW DIAGRAM

Second Phase

The second phase of the analysis, presented in Chapter 13, consists of screening the transport concepts by comparison of the cost/performance measures in relation to the requirements for muck and incoming materials transport. This comparison provides the basis for selection of transport modes which appear to offer potential for material handling in rapid excavation tunneling projects of the future.

Up to this point in the analysis, the systems analyzed have included only the horizontal or vertical transport functions and the analysis has considered only the equipment acquisition and operation cost elements. The analysis of the total material handling function requires that functional systems needed for loading and extending the material handling system in the near-face zone and for transferring material at the shaft station be defined and included in the analytical model. In addition, all life cycle cost elements must be taken into account for each of the functional systems.

Third Phase

The third phase of the analysis includes:

- Development of cost and performance models for the analysis of integrated or total material handling systems, taking into account the total life cycle of the system and all essential functions.

- Development of cost estimating relationships (CER) for each of the life cycle cost elements related to each of the functional systems, in a simple parametric or algebraic form suitable for use in the integrated system model.

The many CERs necessary were generated by a variety of methods. The most desirable method is to relate historical cost data to design or performance parameters. CERs for a number of cost elements in this study were generated in this way. Other cost elements were estimated by projecting crew sizes and applying standard labor rates. Many of the elements of lesser significance were estimated using cost factors based on experience and judgment. Emphasis was placed on achieving relative accuracy among the more significant cost elements rather than absolute accuracy on less important items.

The integrated system model which has been designed to accommodate all life cycle cost elements and functional systems with considerable flexibility is discussed in Chapter 14 and the cost element estimating relationships are summarized in Appendix 3A.

The integrated system model sums, for each cost element, the cost contributions from each functional system included in a specific integrated system. The value used for the cost contribution is established by the system capacity required and the geometry of the tunnel. Rules for summing the cost contributions are established within the model to accommodate various excavation strategies. The cost element sums are then added together to obtain the total system cost.

After summing all costs for a specific integrated system case, the model determines the linear feet of tunnel completed in the defined case and divides the total cost by the total feet of tunnel to obtain a comparative measure of material handling costs. This is referred to as the "figure of merit" for the system since it effectively measures the cost against the end accomplishment of the system; that is, handling the material required to construct a length of tunnel.

Fourth Phase

The final phase of the analysis, presented in Chapter 15, is the comparison of integrated system concepts by generating figures of merit (expressed as cost of materials handling per foot of tunnel) from the integrated system models and cost estimating relationships.

To facilitate studying the effects on system cost of variables such as advance rate, tunnel diameter, tunnel depth, system availability, tunnel length, and material density, the integrated system cost model is designed to accept as input data parametric values for these variables. Precise mathematical relationships are required to transform the parametric input data to the output figures of merit. This appearance of precision, due to the exact numerical values obtained, may be misleading since cost estimates are inherently uncertain. The results of the analysis are, therefore, better thought of in terms of trends or the mean values of bands of results rather than precise values.

The system costs represent direct costs to the contractor to perform the material handling function. Not included are taxes, insurance, profits, overhead, and undefined contingencies. Future costs were not discounted to reflect cost of capital or inflation since the life of the construction project was assumed to be short (on the order of three years or less). For system comparisons these factors tend to cancel out.

Throughout the study, all costs are adjusted to 1970 U. S. dollars by applying cost indices published in the Engineering News Record. Where there are exceptions to this, special notation is made.

MATERIAL HANDLING SYSTEMS

The number of possible combinations of functional systems (transport modes, loading, transfer, etc) which make feasible integrated material handling systems is so large that for analysis, only a representative number of system combinations were developed from those transport modes, discussed in Chapters 1 through 11, that seemed to have the greatest potential. The analysis concentrates on the extensions of conventional material handling equipment and on innovative material handling systems now in pilot stages of development. Systems involving futuristic approaches (for example, air pad suspension, linear induction motor propulsion, or tubed/modular concepts) were not analyzed because of a general lack of data for these systems.

Transport Modes

The transport modes considered to have the greatest potential based on equipment characteristics and state of development and, therefore, included in the cost/performance comparison of transport modes are listed in Table 12-1.

TABLE 12-1

TRANSPORT MODES ANALYZED

Horizontal Transport	Vertical (V) or Inclined (I) Transport
Trough Conveyor	Trough Conveyor (I)
Hydraulic Pipeline	Hydraulic Pipeline (V)
Pneumatic Pipeline	Pneumatic Pipeline (V)
Locomotive Drive System	Cable Drive System (I)
Side-Wheel Drive System	Side-Wheel Drive System (I)
Siderail System	Siderail System (V)
Monorail System	Hoist (V)
Truck System	

Integrated Systems

The integrated or total material handling systems considered in the analysis are divided into two categories; systems for portal access tunnels and those for deep tunnels. A total system may employ a single transport mode for moving materials into and out of the tunnel or it may use two, three, or four transport modes. The system combinations selected for analysis, based on the relative potential for cost performance shown by the comparison of transport modes, are summarized in Table 12-2. Although other feasible combinations are possible, those selected are sufficient to give an indication of the effect of the major parameters and of the results expected from other combinations.

TABLE 12-2

INTEGRATED SYSTEMS ANALYZED

Systems for Portal Access Tunnels	
Material Out	Material In
Side-wheel drive	Side-wheel drive
Trucks	Trucks
Locomotive drive	Locomotive drive
Conveyor	Locomotive drive
Hydraulic pipeline	Locomotive drive

Systems for Deep Tunnels			
Material Out		Material In	
Horizontal	Lift	Lower	Horizontal
Side-wheel drive	Side-wheel drive	Side-wheel drive	Side-wheel drive
Siderail	Siderail	Siderail	Siderail
Monorail	Hoist	Hoist	Monorail
Locomotive drive	Hoist	Hoist	Locomotive drive
Locomotive drive	Cable drive	Cable drive	Locomotive drive
Conveyor	Hoist	Hoist	Locomotive drive
Conveyor	Conveyor	Cable drive	Truck
Hydraulic pipeline	Hydraulic pipeline	Hoist	Locomotive drive

LABOR RATES

Hourly labor rates applied throughout the study are shown in Table 12-3. These are based on rates provided by unions to contractors in the Southern California area and include the basic fringe benefits and wage taxes. Where equipment new to tunneling is employed and no labor category was available to meet the operational requirements of the system, an analogy was made with an established labor category based on an estimated skill level requirement. For larger sized crews an added factor was applied to reflect first-level supervision. Higher levels of supervision and administration are not included in the system cost.

TABLE 12-3

HOURLY WAGE RATES OF TUNNEL CONSTRUCTION CREWS
(For Southern California)

Classification	Hourly Wage Rate (Includes Fringes) (dollars)
Shifter	7.30
Nipper	6.55
Mucking Machine Operator	7.98
Oiler (Hose Tender)	7.10
Motorman	7.98
Brakeman	6.45
Dumpman	6.45
Electrical Foreman	11.07
Electrician	10.35
Compressor Man	7.10
Warehouseman	6.36
Warehouseman Helper	6.22
Carpenter	7.25
Mechanic, Master	9.75
Mechanic, Heavy Duty	8.08
Blacksmith	8.40
Blacksmith Helper	7.66
Drill Doctor	8.08
Powder Man	6.70
Pipe Foreman	10.64
Pipe Fitter	9.67
Track Boss	6.85
Track Crew	6.45
Labor Crew	6.45
Truck Driver	6.50
Walker	8.86
Timekeeper	5.23
Office Men	5.23
Bookkeeper	5.54
Superintendent	12.30
Miner	6.95
Chucktender	6.55

CHAPTER 13

COMPARISON OF TRANSPORT MODES

The analysis of alternate transport modes discussed in detail in Appendix 3B produced two sets of cost/performance data expressed in consistent terms and designated specific cost. The specific cost for capital equipment is expressed as cost per unit of system capacity per unit distance transported. The specific cost of operation is expressed as hourly operating cost per unit of system capacity per unit distance transported. In addition, the transport mode analyses identified the elements of equipment cost and operating cost which make major contributions to the overall cost of the transport system. For example, it was observed that in most cases the cost of operating and maintenance personnel is the controlling element of operating cost for horizontal transport.

These data developed in the transport mode analyses provide a consistent data base in simple parametric form for comparison of transport modes and for input data to the analysis of integrated or total system concepts for material transport in particular tunneling situations. By comparison of the cost/performance data for the individual transport modes, an indication is obtained of those modes worthy of major attention in the development of integrated system concepts. In some cases, where operating and equipment costs are relatively high and there are other disadvantages in practical application, a particular transport mode was not incorporated in the integrated system concepts.

COST/PERFORMANCE MODELS

The analytical models used to generate the cost/performance data for the various transport modes are discussed in detail in Appendix 3B. The model for each transport system consists of two parts, a performance model and a cost model.

Each performance model is designed to determine the performance level of the transport mode from values assigned to a set of design parameters unique to the particular transport system. Examples of these design parameters for the various system types are shown in Table 13-1. The performance of the system is expressed as system capacity in tons per hour for a specified tunnel length (horizontal transport) or vertical depth (vertical or inclined transport).

TABLE 13-1

EXAMPLES OF SYSTEM DESIGN PARAMETERS

System Type	Design Parameters
Conveyors	Belt Speed Width Trough Angle
Pipeline Systems	Percent Solids by Weight Pipe Diameter Velocity of Fluid Specific Gravity of Material Size Gradation of Material
Guideway Systems	Number of Trains, Weight Number of Cars Each Train Car Capacity Top Speed
Free Vehicle Systems	Number of Vehicles Speed of Vehicles Capacity of Vehicles

The cost model consists of two segments; one computes the hourly operating cost, the other computes the equipment acquisition cost. These costs are based on cost estimating relationships (CERs) which have as inputs values of the design parameters which specify the system, or intermediate terms such as horsepower which are computed by the system models. The development of the cost functions for each transport mode is described in Appendix 3B.

The cost per unit performance (tons per hour) is obtained by dividing the performance into the equipment cost (dollars) and into the hourly operating cost (dollars per hour). Each resulting ratio is also divided by the length (in miles for horizontal transport) or the vertical depth (in 1,000's of vertical feet for vertical or inclined lift systems). As a result, two ratios are generated which are indicative of the cost/performance relationship of each system evaluated. The cost/performance ratios are defined as follows:

Horizontal Transport

$$\text{Equipment, Specific Cost} = \frac{\$}{(\text{tons/hr})\ \text{mile}}$$

$$\text{Operation, Specific Cost} = \frac{\$/\text{hr}}{(\text{tons/hr})\ \text{mile}} = \frac{\$}{\text{ton-mile}}$$

Vertical or Inclined Transport

$$\text{Equipment, Specific Cost} = \frac{\$}{(\text{tons/hr})(\text{ft}/1{,}000)}$$

$$\text{Operation, Specific Cost} = \frac{\$/\text{hr}}{(\text{tons/hr})(\text{ft}/1{,}000)}$$

The numerical value of these ratios is a function of the hourly capacity of the system. The results of the system analysis are plots of the above cost/performance ratios against system capacity (tons per hour). In order to convert the specific equipment cost and specific operating cost terms to system equipment cost (dollars) or system operating cost (dollars per hour), the specific cost value must be the appropriate value for the system capacity being considered. After determining either function (specific operating cost or specific equipment cost), the value must be multiplied by the hourly capacity in tons per hour and by the system length in miles or depth in 1,000 feet as appropriate. The use of the more familiar expression (dollars per ton-mile) for operating cost can be misleading if the system capacity is not clearly stated. For this reason, the more precise term [($/hr)/(ton/hr) mile] is used.

SUMMARY COSTS

The results from all transport modes studied show a fairly consistent pattern. Figures 13-1 and 13-2 show typical functions for the operating cost term and the equipment cost term, respectively. As the system capacity increases, the specific costs decrease but tend to level out in the 3,000 ton-per-hour and above range. The "economy of scale" for material handling systems up to this range is clearly evident. For lower tonnage rates, the costs increase rapidly. This phenomenon can be explained, although from system to system the reasons vary somewhat. The guideways represent a fairly fixed set of costs (per unit length) for many systems. As the capacity of the system is decreased, the unit cost for guideway equipment and its maintenance increases. The guideway cost divided by the tonnage rate establishes a parabolic function which tends to level off as the tonnage rate increases. The capacity range studied in the system analysis varies from 7,000 to 100 tons per hour, or 70:1. At 7,000 tons per hour, costs are almost directly proportional to the tonnage being moved and the system length; hence, the specific cost functions tend to remain constant in this range.

The economies of scale can be viewed in another way. The curves of Figures 13-1 and 13-2 imply that specific costs are quite sensitive to advance rate for small-diameter tunnels (since the rate of muck production is relatively low at maximum advance rates), but relatively insensitive to advance rates in the higher ranges for large-diameter tunnels. The specific operating cost for a 10-foot tunnel, for example, would decrease from about $0.09 per ton-mile at an advance rate of 300 feet per day to $0.06 per ton-mile at 1,500 feet per day. For a 40-foot diameter tunnel the decrease at these advance rates would be from about $0.018 to $0.0075.

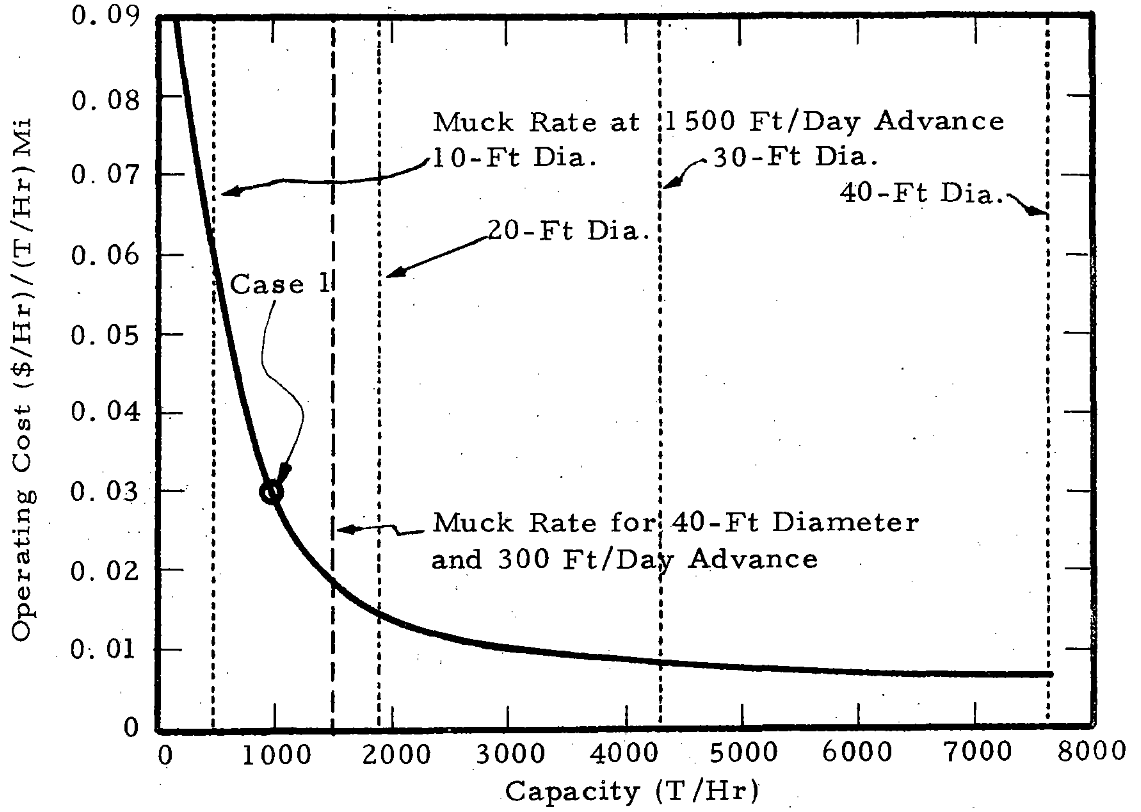

FIGURE 13-1

GENERALIZED OPERATING COST

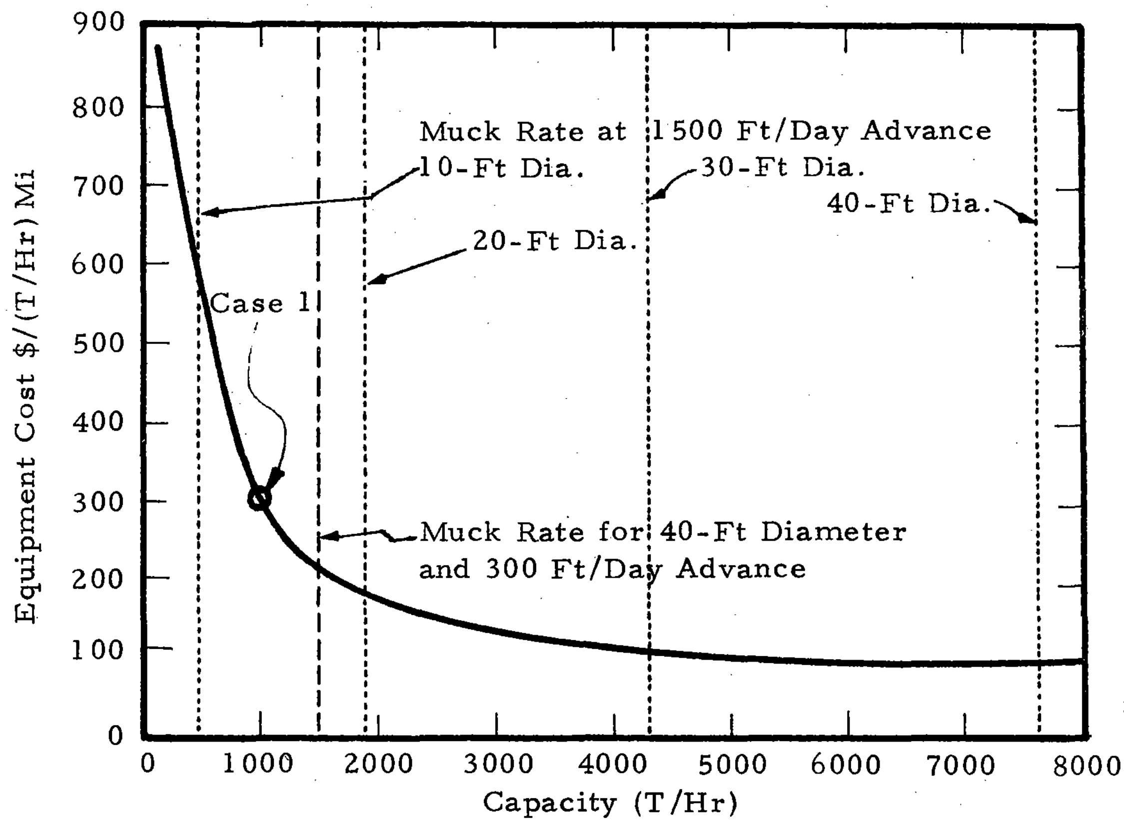

FIGURE 13-2

GENERALIZED EQUIPMENT COST

COMPARISON OF OPERATING AND EQUIPMENT COSTS

The relative importance of operating cost compared to equipment cost can be illustrated by an example from Figures 13-1 and 13-2. For Case 1, the specific operating cost is \$0.03 per ton-mile and specific equipment cost is \$300 per (ton/hr)-mile. If the material handling system is amortized over 10,000 hours, the specific equipment and operating costs are equal as shown by the following calculation:

$$\frac{\$300/(\text{ton/hr})\text{-mile}}{10{,}000 \text{ hr}} = \$0.03/\text{ton-mile}$$

Thus, for less than 10,000 hours of equipment life, the equipment cost would tend to dominate; for more than 10,000 hours of life, the operating cost would be the dominant factor.

Material handling systems may be used for this length of time, but it is impossible to predict an exact life. Ten thousand hours is equivalent to 1.25 years of continuous operation on a 3-shift, 7-day-per-week basis. Over 25 miles of tunnel could be completed in this time period at a continuous advance rate of 300 feet per day. The analysis of integrated systems discussed in Chapter 15 shows that the operating cost generally dominates if the equipment is used on more than 40 miles of tunnel; but to reach this more definitive conclusion, a more complex analysis than that shown for Case 1 is required. Advance rate, tunnel length, availability, salvage value, and the number of tunnel segments excavated by a given set of equipment are all included in the integrated system analysis, but were not considered in Case 1.

It is evident that the economics of permanently installed material handling systems, such as those used in mines, are influenced much more by operating costs than equipment costs, because these systems often have an operating life of 10 years or more.

COMPARISON OF HORIZONTAL TRANSPORT SYSTEMS

Figures 13-3 and 13-4 show the relative costs of the various horizontal transport systems considered. It appears that, of all the systems considered, the side-wheel drive system offers the lowest specific operating cost over a wide range of capacities. At capacities over 1,500 tons per hour, the systems tend to separate into two cost groups with the siderail, conveyor, and truck systems costing more to operate than the locomotive, hydraulic, and side-wheel systems. At 2,000 tons per hour the difference between the lowest and the highest operating cost is about $0.03 per ton-mile. The specific equipment cost curves of Figure 13-4 tend to be flatter; but while they also converge at about 2,000 tons per hour, they begin to diverge at higher capacities. The hydraulic equipment cost remains below the rest of the group at all capacities. Equipment costs for three sizes of locomotive systems, two conveyor speeds, and two truck speeds are shown in Figure 13-4 to show the cost sensitivity to these factors. Since, in most cases, the effect or speed or locomotive size is relatively small, subsequent comparisons show only one set of data for each transport mode. Comparison of transport modes in an integrated system is not straightforward due to the two cost terms (equipment and operations) involved. If operating and equipment costs are both low or both high, the system cost will be correspondingly low or high. But if one is high and the other low, the relative merit of the system may be effected by the length of the tunnel and the total hours of use.

Figures 13-5 and 13-6 show system absolute costs for a 10-mile long horizontal transport system. These data were derived from Figures 13-3 and 13-4, respectively. Comparisons at other distances can be derived easily in a similar manner. It appears that for most transport modes except trucks, costs are approximately proportional to capacity. Trucks require one of the lowest investments at low capacities and the highest investment at high capacities. Differences generally are not great, however. At 1,000 tons per hour the range is from slightly under one million dollars for hydraulic to $3.7 million for siderail. Operating costs are also rather tightly grouped with the exception of the siderail and truck systems at higher capacities.

One of the most significant characteristics shown for the system costs is the gradual slope of both the equipment cost and the operating cost curves. This is basically a reflection of the economy of scale phenomenon. The analysis of integrated systems presented in Chapter 15 shows that the flatness of the operating cost curves, and to a lesser degree the equipment cost curves, dominate the analysis and cause the material handling costs for tunnels between 10 feet and 40 feet in diameter to be

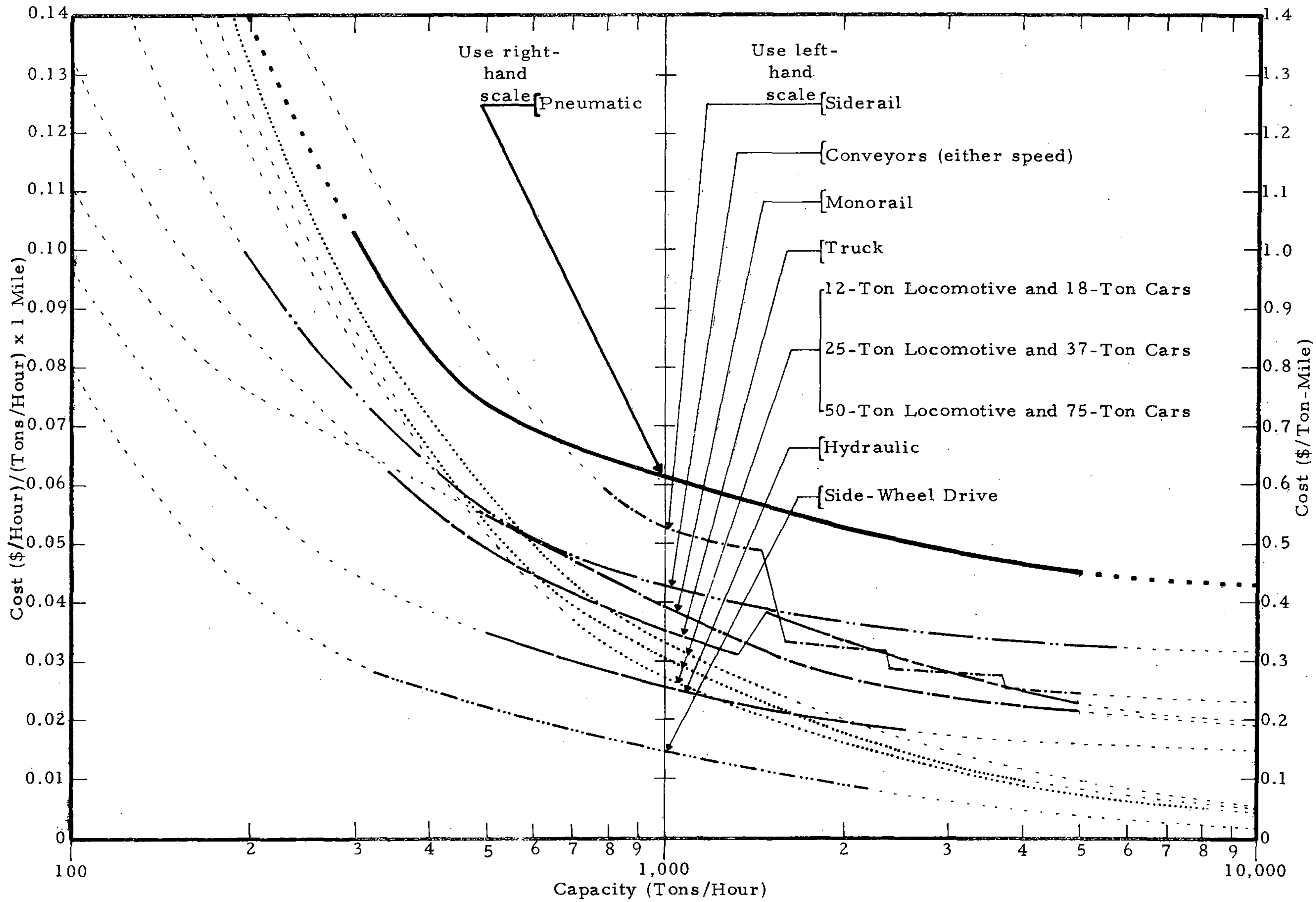

FIGURE 13-3

OPERATING COST COMPARISON FOR HORIZONTAL TRANSPORT SYSTEMS

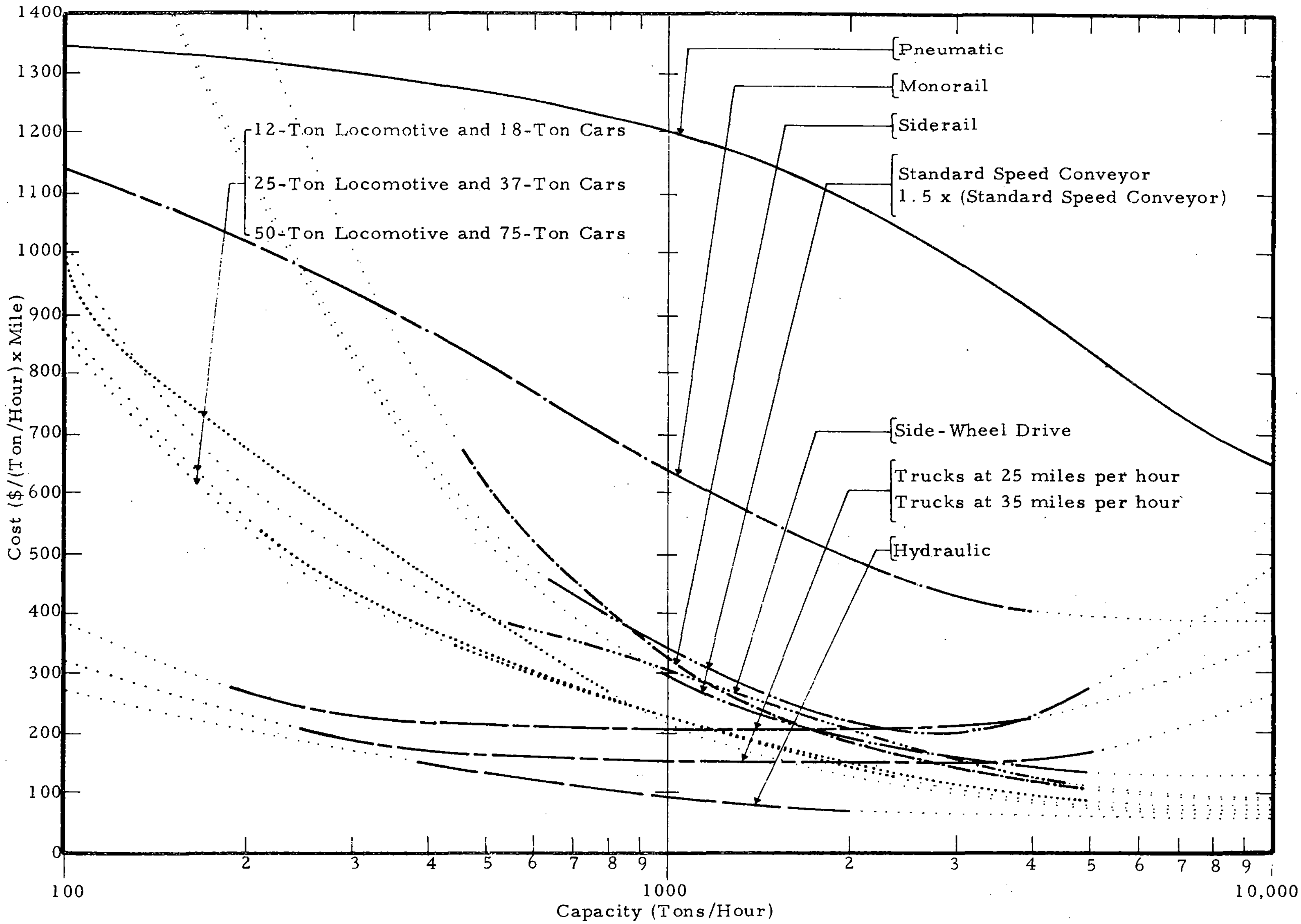

FIGURE 13-4

EQUIPMENT COST COMPARISON FOR HORIZONTAL TRANSPORT SYSTEMS

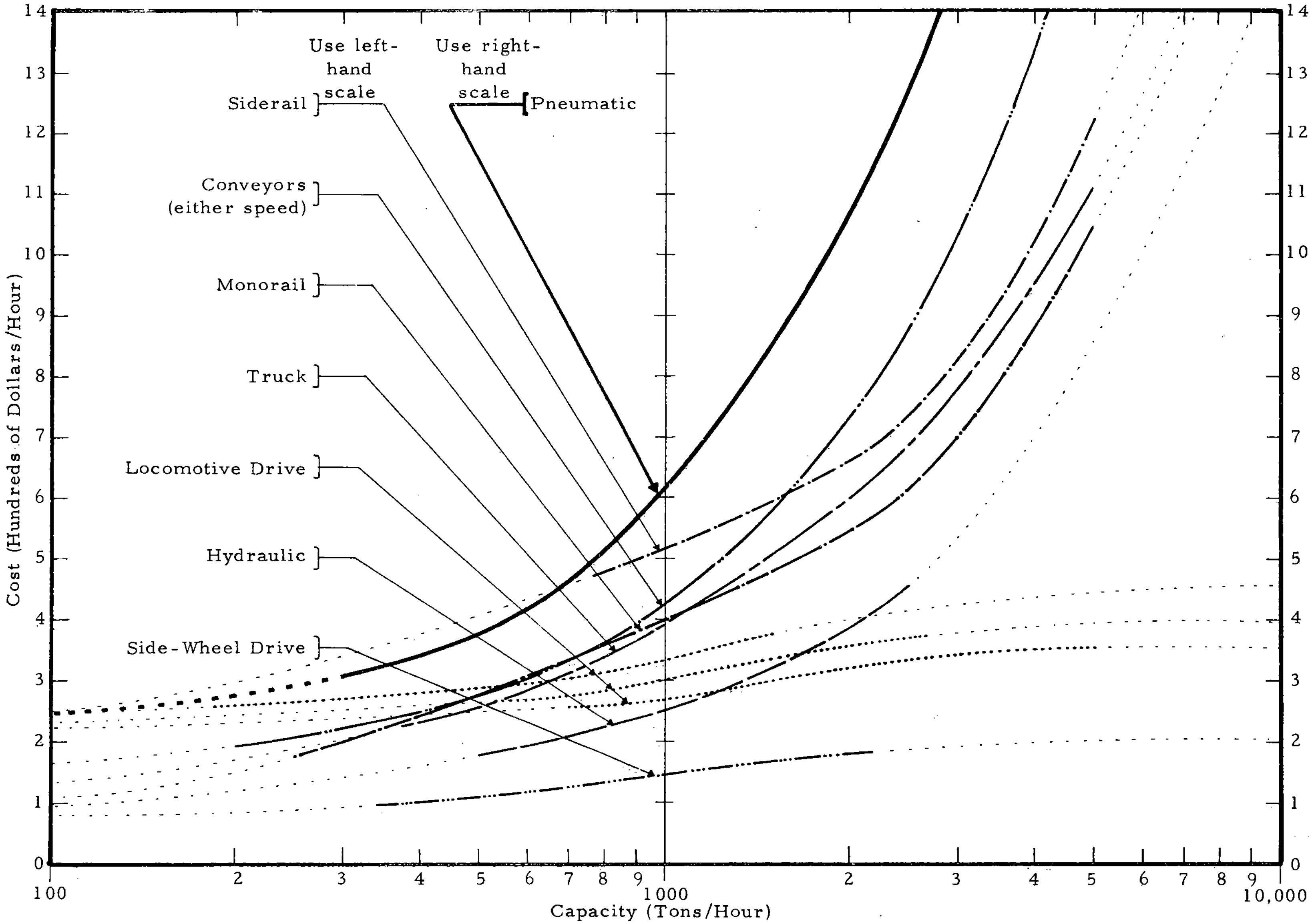

FIGURE 13-5

OPERATING COST COMPARISON FOR 10-MILE HORIZONTAL TRANSPORT

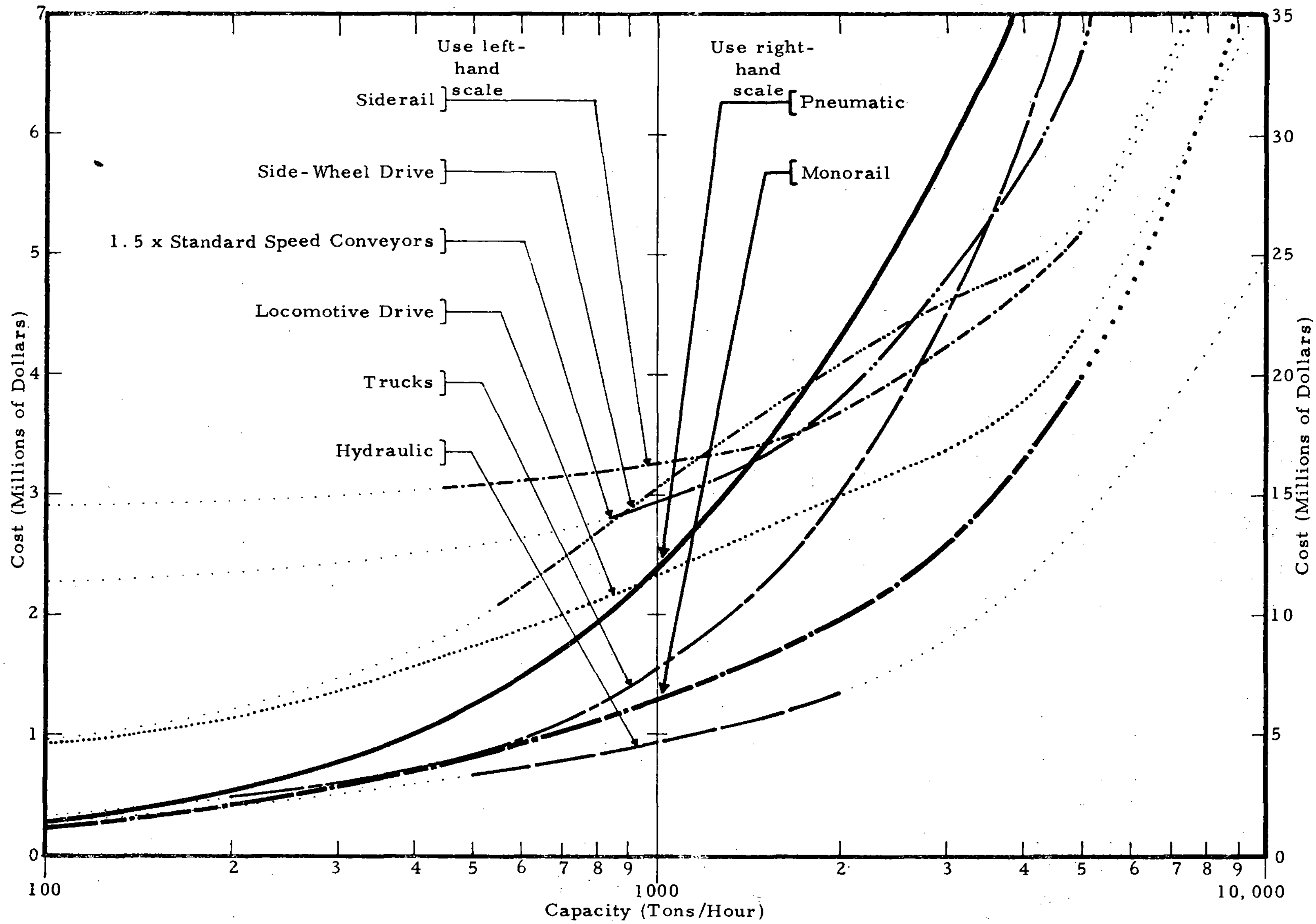

FIGURE 13-6

EQUIPMENT COST COMPARISON FOR 10-MILE HORIZONTAL TRANSPORT much more constant than anticipated. Even when system capacities vary from 100 tons per hour to as much as 5,000 tons per hour - a ratio of 1 to 50 - both operating and equipment costs increase by a factor of 10 or less.

The basic data presented here for the side-wheel drive system were derived independently by the manufacturer of SECCAM.* These data were accepted and used as provided because they appeared to be reasonable for a highly automated, low maintenance system. It is unlikely that adjustments in these data would change the economy-of-scale characteristics, such as the slope of the cost functions, reflected in the specific and absolute costs. The more likely effect would be to move the curve upward in relation to the other transport modes.

The operating cost data for the conveyor subsystem is considered highly reliable. Conveyor equipment costs are well known and the conveyor performance potential is well established.

The locomotive drive system costs are also based on good data for equipment and operating costs. The performance model assumptions may be overly optimistic, but it is more likely that changes here would bias the cost curve rather than affect its other characteristics.

The confidence placed in the siderail, truck, and hydraulic systems data is not as high as for the other transport modes; but costs for these systems appear consistent with the assumptions described in Appendix 3B.

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*Tradename for system developed by Societe Industrielle de Lattre-LeVivier, France.

COMPARISON OF VERTICAL TRANSPORT SYSTEMS

Figures 13-7 and 13-8 show comparisons of the various transport modes considered appropriate for vertical or inclined transport. A greater spread appears in these data than for the corresponding cases for horizontal transport, but actual ratios of equipment costs at 1,000 tons per hour do not vary more than fourfold for the four lower cost systems. Similarly, operating costs for the four lower cost systems are grouped within a factor of three.

Selecting the most cost effective vertical or inclined lift system based on specific costs is as difficult as it is for the horizontal systems. The choice will be determined by factors other than system cost, such as the compatibility of the lift system with the horizontal transport system, availability of inclined shafts, and shaft costs chargeable to the material handling system. The final choice must be made by considering the integrated system at a more inclusive level than presented in this report.

Figures 13-9 and 13-10 are derived for a 1,500 foot depth from data on Figures 13-7 and 13-8, respectively. Similar comparisons for other depths can be derived in a similar manner. These again reflect the economy of scale phenomenon in a different form. The slopes of these curves are greater, in most cases, than those presented for horizontal systems, but the costs continue to increase at a slower rate than the increase of the material handling flow rate. The operating cost for conveyors is higher than for other transport modes at high flow rates because maintenance costs were assumed to be proportional to the amount of material handled. Equipment costs show variations similar to operating costs; however, there are systems which have high operating costs but low equipment costs (e.g., conveyors). The equipment required at the bottom of the shaft to transfer material to the vertical transport system is generally not included in the system cost, but these are significant in the integrated system equipment costs.

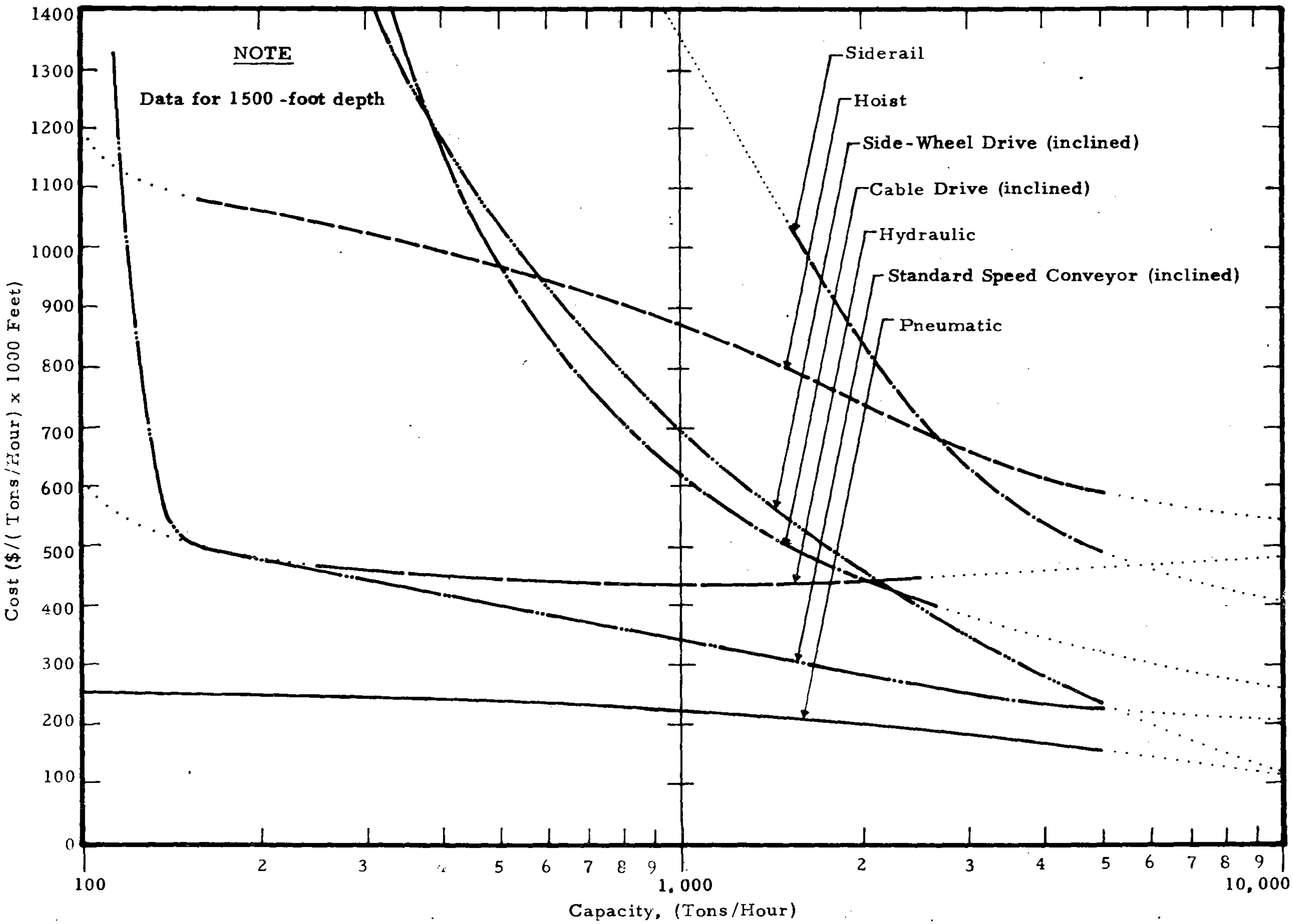


FIGURE 13-7

EQUIPMENT COST COMPARISON FOR VERTICAL AND INCLINED TRANSPORT SYSTEMS

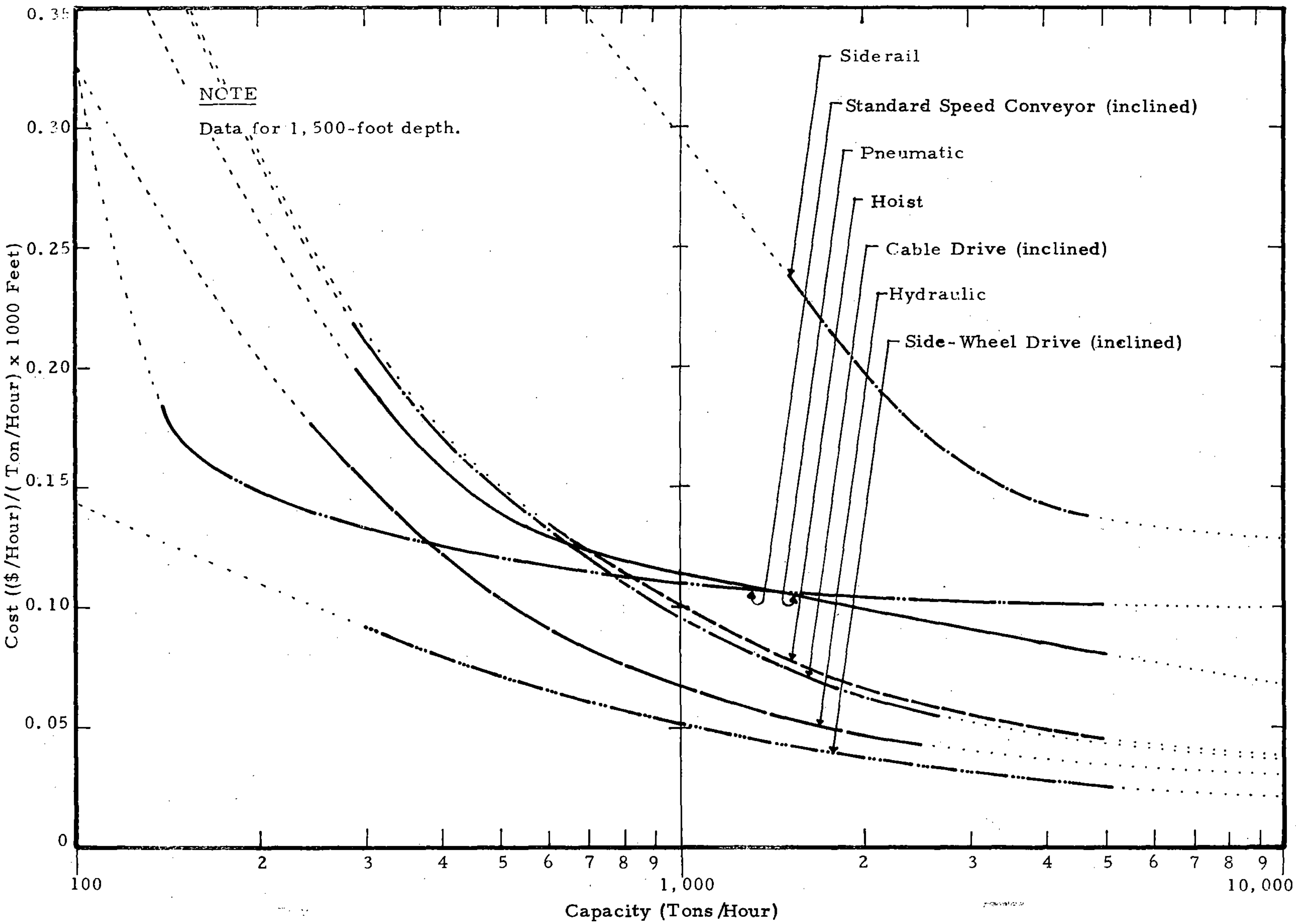


FIGURE 13-8

OPERATING COST COMPARISON FOR VERTICAL AND INCLINED TRANSPORT SYSTEMS

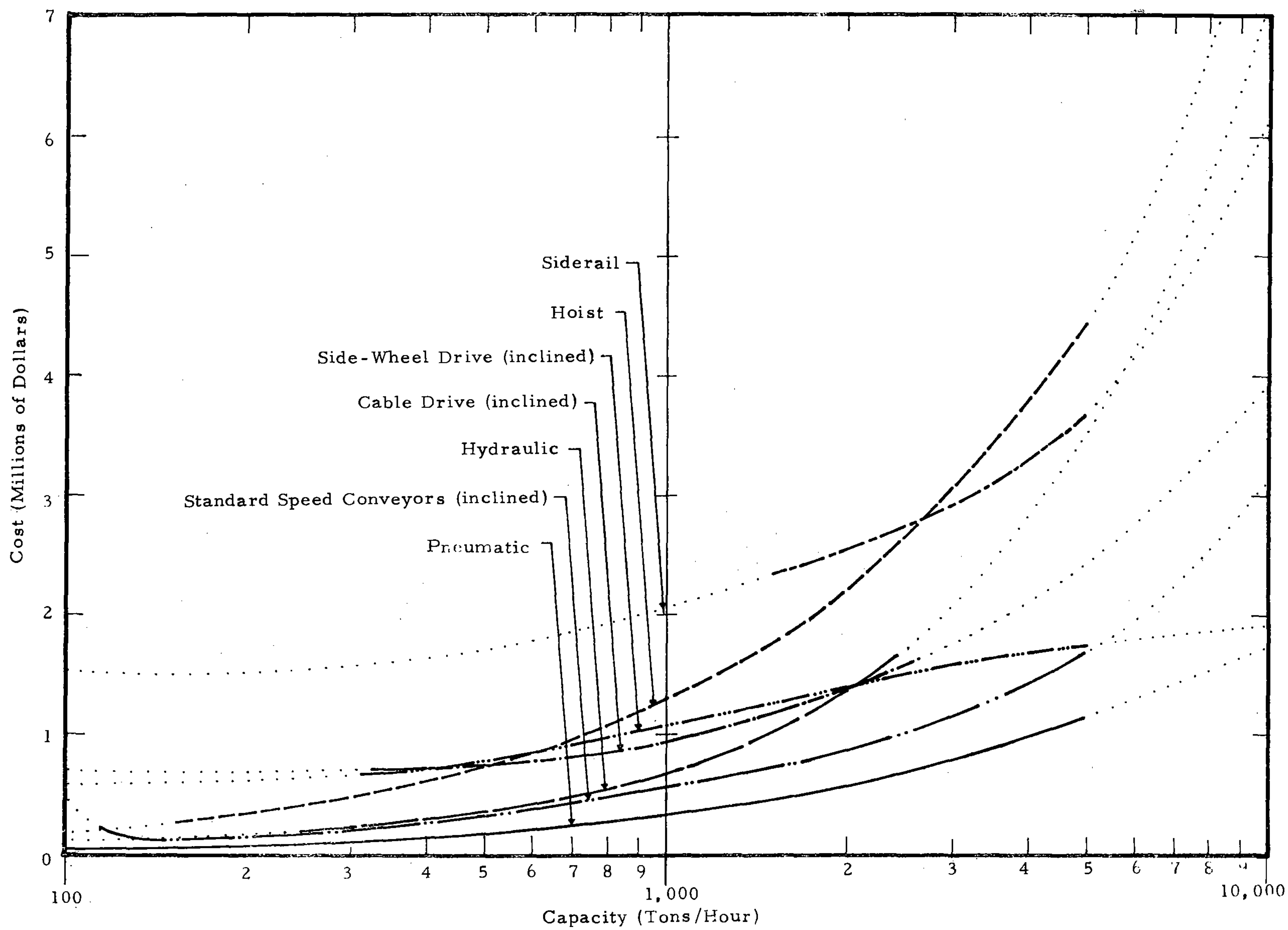


FIGURE 13-9

EQUIPMENT COST COMPARISON FOR 1,500-FOOT VERTICAL TRANSPORT

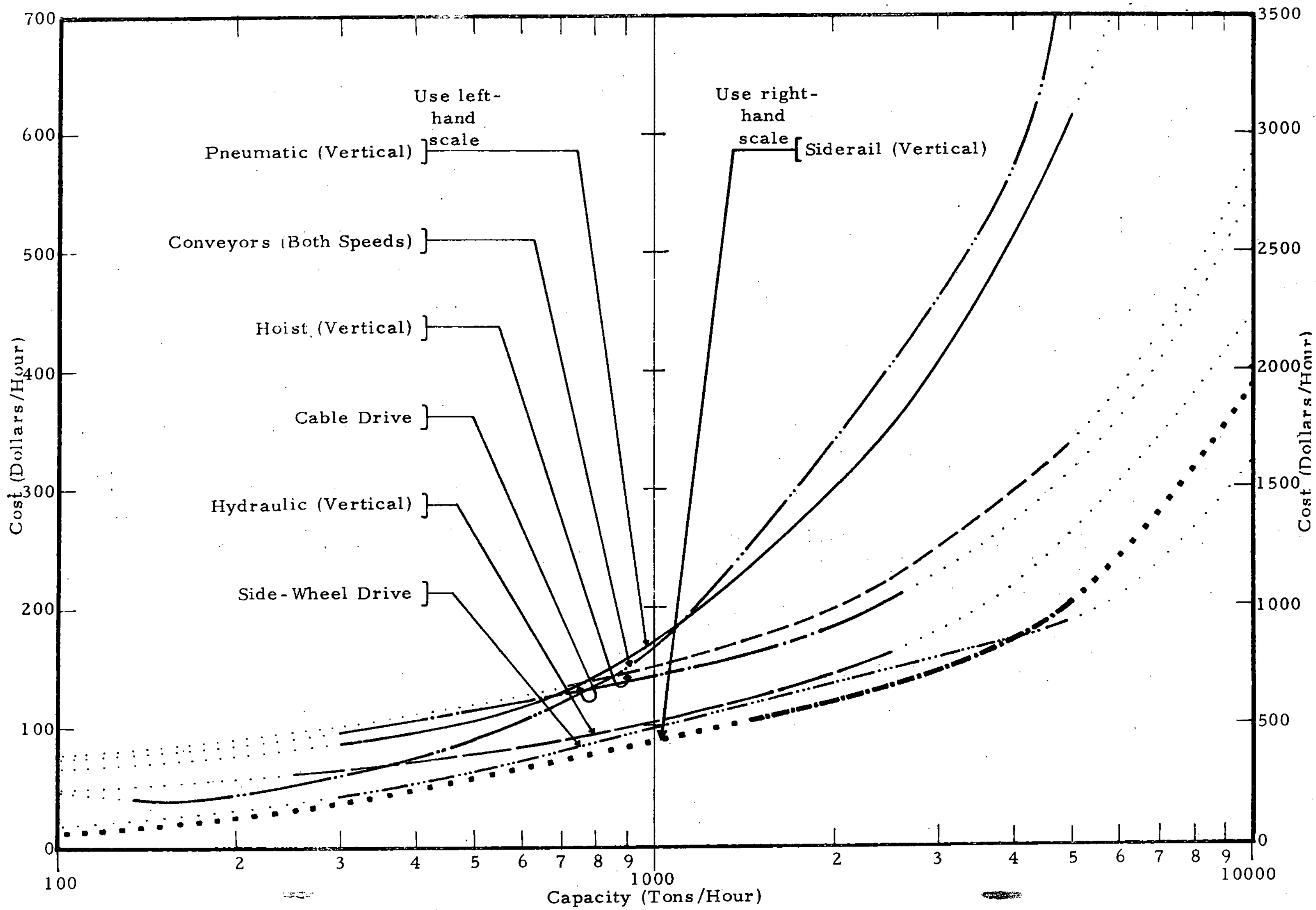


FIGURE 13-10

OPERATING COST FOR 1,500-FOOT VERTICAL TRANSPORT

CHAPTER 14

INTEGRATED SYSTEMS MODEL

The integrated system model is designed to accept cost data generated by the system cost models for the various modes of transport selected for horizontal and vertical transport and combines these cost data with cost data for transport system extension, loading, and intermode transfer at the shaft station. "Integrated systems" are "constructed" out of transport, extension, loading, and transfer systems by selecting a logical combination of these systems. Integrated system costs are obtained by summing appropriate system costs for the advance rate, diameter, tunnel configuration, construction strategy, and other factors which define the case being studied. A summary discussion of these factors is given in Chapter 1.

The material handling integrated system can be used for any number of tunnel segment construction cycles within the life span of the system equipment until the equipment is sold or salvaged. Equipment costs are amortized over the sum of these use cycles to obtain the equipment cost per foot of tunnel or per ton of material moved.

The location of the various material handling functions for muck removal in a typical tunneling configuration using a dual heading strategy is shown in Figure 14-1. Each of these functional systems is incorporated into the material handling integrated system model except in some cases when a particular system may not be appropriate. For example, if the same mode of transport is used for both the horizontal and vertical attitudes, no intermode transfer system would be required.

If the transport mode (or modes) used to remove muck cannot be used for incoming materials, another set of systems for this purpose can be included in the integrated system model. For example, if a hydraulic system were used to remove muck, truck and hoist systems might be used to transport the incoming materials. For the configuration and strategy of Figure 14-1, the additional functional systems incorporated in the integrated system model to account for the incoming material flow are shown in Figure 14-2.

Any number of functional systems can be included in the integrated system model, although eight systems are about the maximum needed to "construct" a total system. Typically, fewer functional systems are required if transport modes are used which are capable of handling material in both directions on the same equipment.

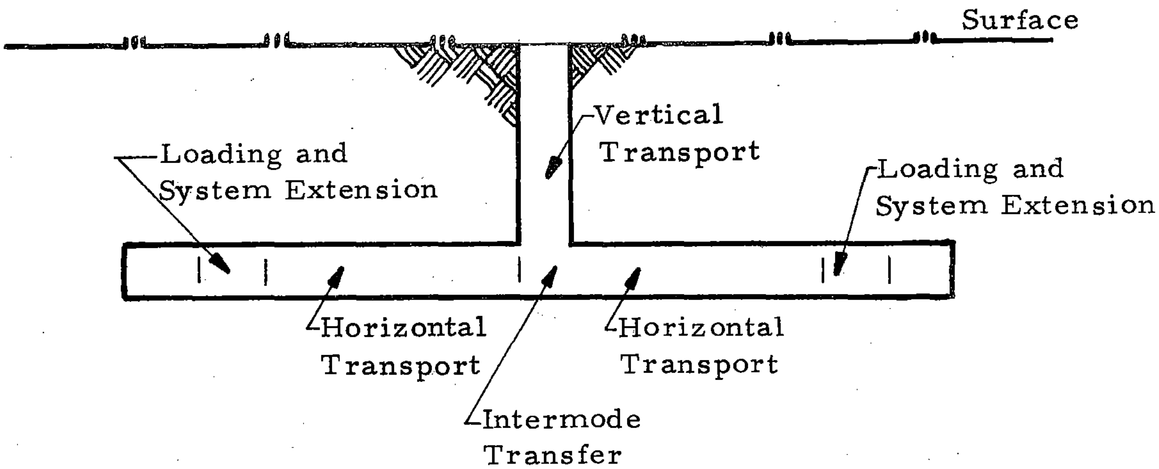


FIGURE 14-1

MUCK REMOVAL FUNCTIONS

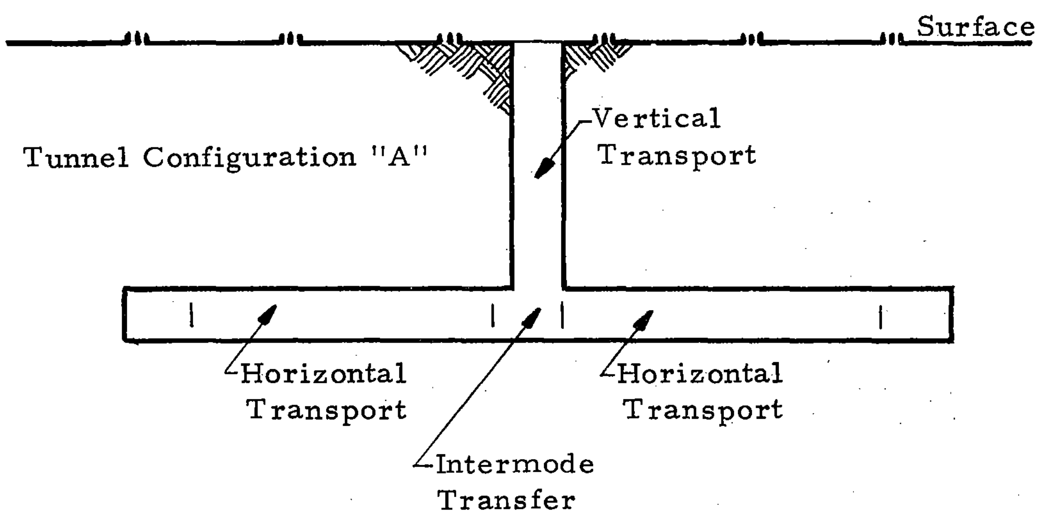


FIGURE 14-2

INCOMING MATERIAL TRANSPORT FUNCTIONS

TUNNEL CONFIGURATIONS AND CONSTRUCTION STRATEGIES

By selecting the appropriate combinations of functional systems, a number of tunnel configurations and construction strategies can be studied. Configuration refers to the geometry of the tunnel complex, and strategy refers to the sequence in which equipment is shifted from segment to segment of the tunnel and the number of material handling systems operating simultaneously. Sketches are shown in Figure 1-8 for cases which cover almost any tunneling situation. The particular cases studied using the integrated system model are illustrated in Figures 14-1 through 14-7. A variation in the tunnel construction strategy implied for configuration A, shown in Figure 14-2, is shown in Figure 14-3. In this variation, rather than excavate simultaneously at two headings, segment B is excavated after segment A has been completed, but the same vertical transport system is used.

Material handling systems which are not satisfactory for vertical shafts but work well in inclined shafts require variations of these configurations. The model is not restricted to vertical shafts. Assuming that appropriate systems have been selected and that an inclined shaft is practical, the model may be used in any given configuration. Configurations which illustrate inclined shafts are shown in Figure 4-14.

The simple portal configuration, which is typical of tunnels for surface transportation systems, is shown in Figure 14-5.

The complete length of a tunnel project can be studied by combining in the appropriate way data generated from studies on the individual configurations shown. A feature in the integrated system model provides for repeated reuse of the material handling system on like tunnel configurations. This feature was included to show the effect that repeated use of material handling equipment has on material handling cost, that is, the effect of amortization of equipment cost over a number of tunnel segments. For example, configuration A might be repeated for several tunnel segment construction cycles as shown in Figure 14-6. A construction cycle consists of getting the equipment in place and ready for use; its use, maintenance and extension for the length of the tunnel segment; and removal of the equipment at the end of the construction period.

A variation of tunnel construction strategy is shown in Figure 14-7 which will yield the same tunnel configuration but different construction costs because mobilization costs are adjusted to reflect the strategy.

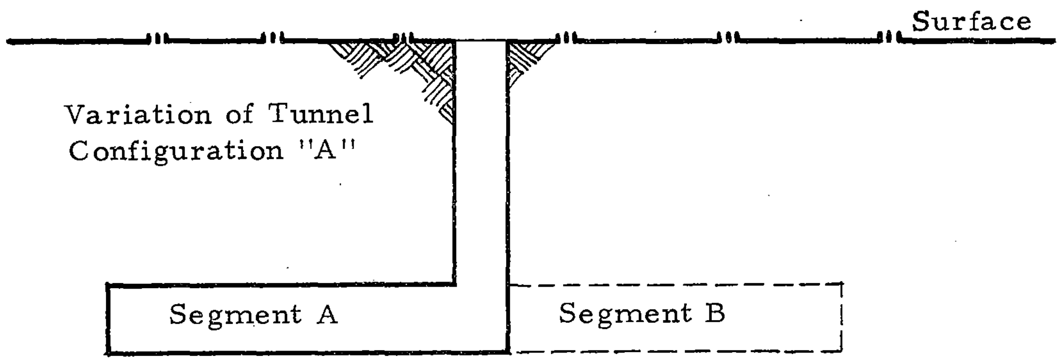


FIGURE 14-3

VARIATION OF TUNNEL STRATEGY

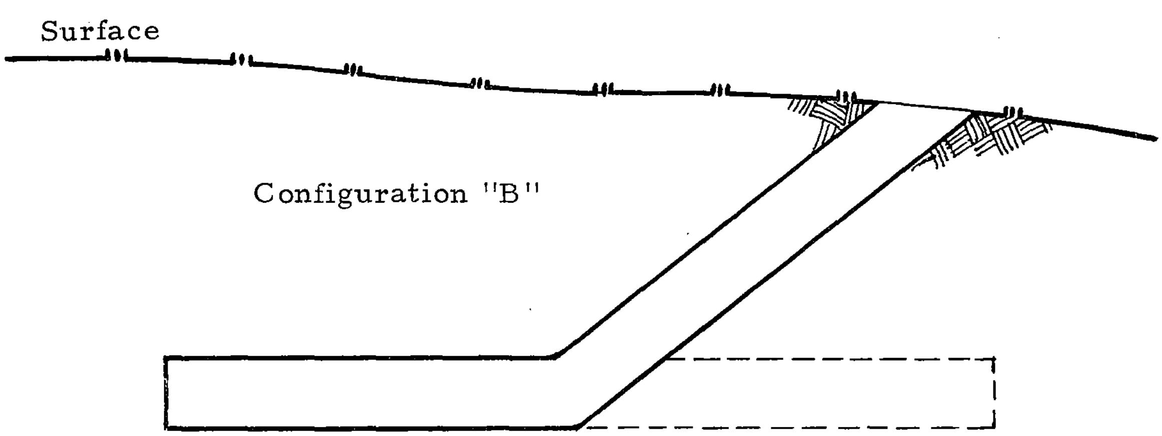


FIGURE 14-4

INCLINED SHAFT CONFIGURATION

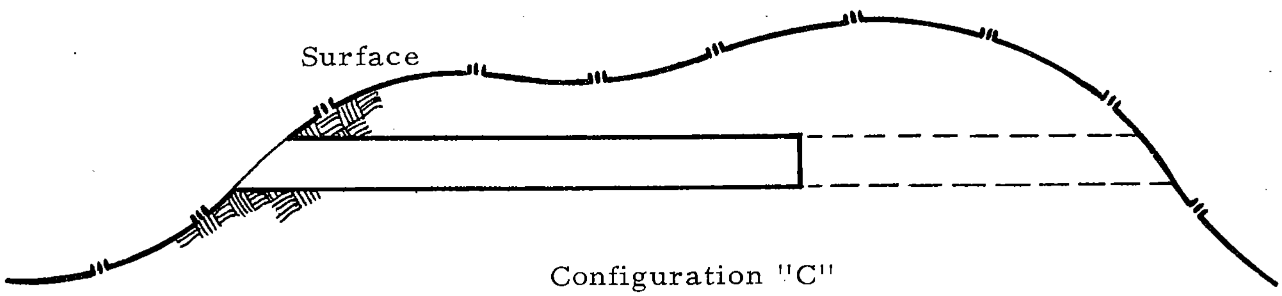


FIGURE 14-5

PORTAL TUNNEL CONFIGURATION

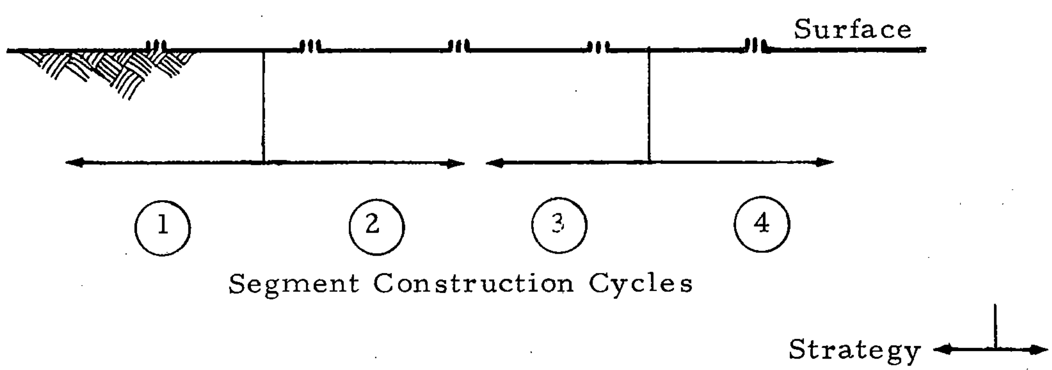


FIGURE 14-6

BIDIRECTIONAL CONSTRUCTION STRATEGY

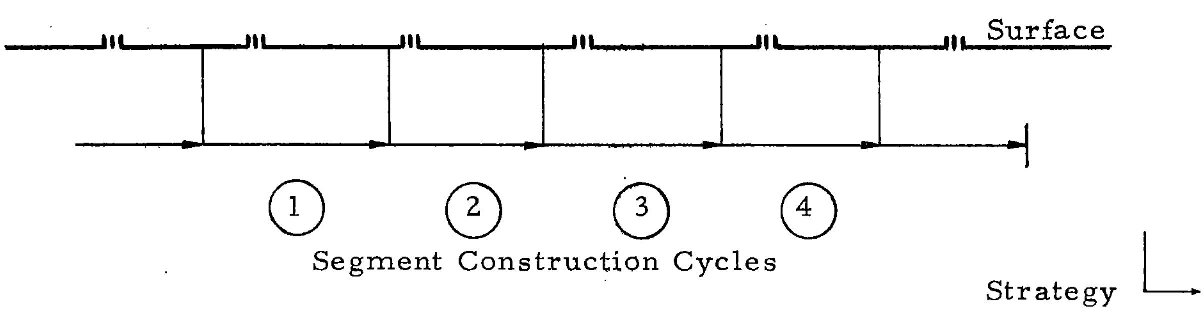


FIGURE 14-7

SINGLE DIRECTION CONSTRUCTION STRATEGY

DEFINITION OF TERMS AND EQUATIONS

The analytical nature of the integrated system model requires that cost and performance related parameters be quantified. The performance required of the material handling system is defined by specifying the geometry of the tunnel, advance rate, and material density. The following terms are parameters defined for use in the integrated system model.

A = Advance rate (feet per 24-hour day) of the tunnel face. Advance rate and tunnel diameter (D) determine the design capacity of the material handling system.

A_6 = Series availability of individual material handling systems. The term "series availability" is used to make a distinction between the availability of the system and the availability of the components of the system.

πA_6 = Product of the series availabilities of all material handling systems used in an integrated system.

A_7 = Availability of the excavation machinery and all other critical, nonmaterial handling functions. Assumed to be 0.7 in the 1975-1980 time frame.

D = Unlined bore diameter (feet) of the horizontal tunnel segment. For horseshoe shaped tunnels, the dimensions of the horseshoe are picked to achieve an area match with the preselected circle.

D_1 = Tunnel depth (feet), measured from the horizontal tunnel floor to the ground level at the shaft location. For inclined shafts it represents the vertical rise of the incline. For portal tunnels, $D_1 = 0$.

K = Ratio of equivalent mass of material moved in (T_2) and mass of muck removed (T).

K_2 = Ratio of volume occupied in transit by the incoming material and mass of the same material (cubic yards/ton).

L = Length of the horizontal tunnel segment (miles).

L_5 = Tunnel length (feet) required for loading and extension of the material handling system.

M = Number of tunnel segments in which a specific set of material handling equipment is used.

M_4 = Ratio of time and effort required for partial movement and reinstallation of horizontal transport systems compared to that required for complete removal and reinstallation for each tunnel segment, including lifting equipment to the surface and installing it through another shaft.

M_5 = Same ratio as M_4 but assigned values appropriate for loading/ extension systems.

M_6 = The reciprocal of the number of tunnel segments served sequentially by a single shaft, that is, the number of segments constructed sequentially per shaft. This defines the ratio between the number of relocations of shaft-related equipment and the number of relocations of the horizontal transport equipment.

N = Number of tunnel excavation systems feeding simultaneously to each shaft material handling system.

R_7 = Mean density (tons/cubic yard) of the in-situ rock.

S_1 = Project operating time (hours) required for a tunneling system from beginning of excavation to end of excavation for a particular tunnel segment. The number and duration of operating shifts per day and number of work days per week determine the operating time per calendar period. The operating time corresponds to the hours for which work crews are paid.

S_2 = Material handling system operating time (hours) during S_1. This is the time the material handling system is consuming energy and is less than S_1 due to downtime during the project operating time (S_1).

S_7 = Grade of inclined shafts (ratio of rise over run; sometimes expressed in percent).

T = Muck mass removal rate (tons per hour).

T_1 = Incoming materials mass flow rate (tons per hour).

T_2 = Incoming materials equivalent mass flow rate (tons per hour). Equivalent mass is the weight of in-situ muck which would occupy the same volume as that occupied by the incoming materials in transit.

T_3 = Muck mass removal rate (tons per hour) through a shaft with N excavation system operating and feeding the shaft.

Equations defining the basic material flow rates and operating times are:

$$S_1 = (5{,}280\,L)/(A/24)(A_7 \pi A_6)$$

$$S_2 = S_1(A_7 \pi A_6)$$

$$T = 3.14(D/2)^2 (A/24)(R_7/27)$$

$$T_2 = T_1 \times K_2 \times R_7 = T \times K$$

$$T_3 = N \times T$$

Equipment Movement Cycles

The factor M is defined as the number of tunnel segments in which a specific set of material handling equipment is used. This is also the number of use cycles for the equipment. The tunnel segment length (L) and number of use cycles (M) define the total length of tunnel for which a designated set of equipment will be utilized and over which its cost is amortized. This total length is given by

$$L \times 5{,}280 \times M = \text{total length (feet)}.$$

The use factor (M) is applied to all operating, energy, setup, mobilization, and shakedown cost elements used in the integrated system cost model.

It is desirable to compare costs for a number of cases, each of which represents a particular tunnel strategy and tunnel configuration. This requires that, before being multiplied by M, numerical values of mobilization, setup, and shakedown cost elements be adjusted to reflect the relative degree of effort and frequency of moves imposed by reusing the various material handling systems on a number of tunnel segments under the conditions defined for the particular case. These adjustments are applied to groups of systems that can be treated uniformly.

One such group of systems consists of the vertical (or inclined) transport and intermode transfer systems. M_6, which defines the ratio of relocations of shaft equipment to relocations of horizontal transport equipment, is applied to this group. For example, if one tunnel segment is constructed per shaft installation, $M_6 = 1$; if two are constructed per shaft, $M_6 = 0.5$; and if four are constructed, $M_6 = 0.25$.

Other groups of systems which may be treated uniformly are the horizontal transport systems group and the loading/extension systems which work in the near-face zone. M_4 and M_5, the ratios of partial movement to complete removal and reinstallation, are applied respectively to these groups of systems. The values assigned for M_4 and M_5 are:

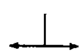
- Advancing system continuously in one direction:

  Strategy 

  M_4 = 0.2 to 0.4 (value used depends on transport systems used)

  $M_5 = 1/(M - 1)$

- Sequential excavation in two directions followed by complete removal of equipment through the shaft and reinstallation through another shaft.

  Strategy 

  $M_4 = 0.6$

  $M_5 = 0.7$

Cost Estimating Relationships

Cost estimating relationships are developed for each material handling functional system which is desired to be investigated as a functional element of a total material handling system. The pneumatic transport mode is not included in the initial list for this investigation due to its unusually high operating cost revealed in Chapter 13 by the comparison of transport modes. These relationships consist of a set of tables or analytical expressions which describe the various cost elements of the particular operational function. Cost estimating relationships are developed and summarized in Appendix 3A for the following functional systems.

Loading/Extension Systems

- Sliding floor
- Short conveyors
- Loading of locomotive drive system
- Loading of side-wheel drive system
- Loading and extension of siderail or monorail system
- Extension (tracklaying) of conventional rail systems
- Loading and extension of hydraulic systems
- Crushing for hydraulic system
- Extension of conveyor

Horizontal Transport Systems

- Locomotive drive
- Side-wheel drive
- Siderail
- Truck
- Conveyor
- Hydraulic
- Monorail

Intermode Transfer Systems

- Conventional rail or truck to hoist
- Conveyor to hoist
- Conveyor or horizontal siderail to vertical siderail

Vertical Transport Systems

- Siderail
- Hoist
- Hydraulic

Inclined Transport Systems

- Side-wheel drive
- Cable Drive
- Conveyor

For each of the above systems, the following cost elements related to the elements of the system life cycle are described in Appendix 3A.

C_1	=	Operating Cost	\$/hour
C_2	=	Equipment Cost	\$
C_3	=	Energy Cost	\$/hour
C_4	=	Setup Cost	\$
C_5	=	Mobilization Cost	\$
C_6	=	Engineering or Development Cost	\$
C_7	=	Training and Shakedown Cost	\$
C_8	=	Disposal or Salvage Value	\$
C_9	=	Spares to Maintain	\$

Each of these cost elements is computed where appropriate for each system included in each case analyzed. The cost element dependent variable or value is a function of one or more of the following independent variables:

$$D, A, L, D_1, T, L_5, T_2$$

Summary values for each of the cost elements are obtained by adding the values of the appropriate cost element for all functional systems comprising the muck removal system. Similarly, the cost elements for the functional systems used in the incoming material handling system are summed. The operating labor costs are multiplied by the project operating time (S_1), and the energy costs are multiplied by the material handling system operating time (S_2). These summation functions are:

$$X_1 = \Sigma C_1\text{'s} \times S_1$$

$$X_2 = \Sigma C_2\text{'s}$$

$$X_3 = \Sigma C_3\text{'s} \times S_2$$

$$X_4 = \Sigma C_4\text{'s}$$

$$X_5 = \Sigma C_5\text{'s}$$

$$X_6 = \Sigma C_6\text{'s}$$

$$X_7 = \Sigma C_7\text{'s}$$

$$X_8 = \Sigma C_8\text{'s}$$

$$X_9 = \Sigma C_9\text{'s}$$

After the summation of cost elements, total system costs are computed using the appropriate application of the equation

$$Z = MX_1 + X_2 + MX_3 + MX_4 + MX_5 + X_6 + X_7 - X_8 + X_9$$

For the operational situation in which a transport mode handles muck only, the C values are functions of T, and Z represents the total cost for muck removal. If a transport mode simultaneously handles incoming material and muck, the C values are functions of $(T + T_2)$, and Z represents the total cost of handling both the inflow and outflow of materials. For a separate transport mode handling only incoming materials, the C values are functions of T_2, and the total cost of handling the incoming materials obtained from the above equation is designated Z_1.

Figure of Merit Computations

The cost of material handling per foot of tunnel (Z_2) has been used as a figure of merit for muck removal in previous tunneling studies. It is a logical basis for comparison of systems. In this model it is used to represent the cost of both muck removal and handling incoming material.

$$Z_2 = (Z + Z_1)/L \times 5{,}280 \times M$$

Cost per ton of muck removed also can be computed by the model. This is of interest since it shows the economy of scale effects better than the cost per foot measure. It is computed by

$$Z_3 = Z/(T \times M \times S_2)$$

Cost of bringing material into the tunnel also can be computed by the model. This is expressed in terms of cost per equivalent cubic yard rather than tons per hour by

$$Z_4 = Z_1/(T_2/R_7)MS_2$$

The system cost routines used in the integrated system cost model include a cost factor, estimating function, or table of values for each of the system cost elements. The cost elements included in each system routine are defined in Appendix 3A. The major cost expressions are derived from the system models developed in Appendix 3B for the horizontal and vertical or inclined transport systems. The expressions or tables used in the integrated system model are simplified estimating relationships derived from the results of the analysis of the individual transport systems.

For all other cost expressions, cost factors and cost estimates are derived from basic information. While a high degree of consistency has been attained in accounting for costs, it was impractical to eliminate some exceptions. The general rule followed is to allocate costs to those functional systems shown in Figure 14-1 and to include all costs for equipment, labor, energy, et cetera, incurred within the functional zone in which the system is operating. An example of this division of costs is illustrated by the locomotive drive system. The cost of track material, cars, locomotives, and maintenance of these components is allocated to the horizontal transport system (or zone). The cost (labor) of laying the track is allocated to the loading/extension zone system although it might have been assigned to the horizontal transport system.

The goal was to keep system costs proportional to the following variables:

Horizontal Transport	=	f (length, tons/hour, time)
Vertical Transport	=	f (depth, tons/hour, time)
Loading/Extension	=	f (advance rate, tons/hour, tunnel diameter and time)
Intermode Transfer	=	f (tons/hour, time) .

Since these variables are often dependent, functions reflecting their dependence are sometimes used. The model uses tables with tunnel diameter and advance rate as independent variables. The tables are set up to be used for discrete values of these variables, which limits the use of the model to discrete diameters and advance rates. The basic format is shown in Table 14-1.

TABLE 14-1

MODEL INPUT DATA FORMAT

Advance Rate (A) (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	$X_{300, 10}$	...	...	...
500	...	...	...	...
750	...	...	...	...
1,500	...	...	...	$X_{1,500, 40}$

Table 14-2 is a summary of data sources used to define the cost elements which are direct inputs to the system model, that is, the inputs described in Appendix 3A.

TABLE 14-2

DATA SOURCES

Item	Extension and Loading	Horizontal Transport	Vertical Transport
Operating, Equipment, and Energy Costs	(a)	(b)	(c)
Setup	(d)	(d)	(d)
Mobilization	(d)	(d)	(d)
Engineering and Development	(e)	(e)	(e)
Training and Shakedown	(d)	(d)	(d)
Disposal or Salvage	(d)	(d)	(d)
Spares to Maintain	(e)	(e)	(e)

(a) Historical Data, Projections, Construction Estimates

(b) Derived from Subsystem Models, Tables or Curve Fits

(c) Derived from Subsystem Models Multidimensional Curve Fits

(d) Construction Estimates

(e) Engineering Estimates

CHAPTER 15

EVALUATION OF INTEGRATED SYSTEMS

INTRODUCTION

This chapter contains the results obtained from the integrated system cost model described in Chapter 14. A number of cases for tunnels with circular bore were studied. The values assigned for several of the input parameters defined in detail in Chapter 14 were usually held constant for the cases studied; exceptions are always indicated. These constant values are:

• Construction strategy		
• Excavation system availability	A_7	= 0.7
• Grade of inclined shafts (rise/run)	S_7	= 0.26
• In-situ rock density (tons/cubic yard)	R_7	= 2.25
• Material flow rate (equivalent weight in/out)	L	= 0.28
• Number of equipment use cycles	M	= 4
• Number of excavation systems simultaneously feeding a shaft	N	= 1
• Tunnel segment length (miles)	L	= 10

Other parameters which were assigned several discrete values over the ranges of interest are:

	Range
• Tunnel advance rate (feet/day)	$300 < A < 1,500$
• Amortization base (miles of tunnel)	$20 < A_b < 80$
• Tunnel diameter (feet)	$10 < D < 40$
• Tunnel depth (feet)	$500 < D_1 < 3,500$

The tunnel advance rate (A) is the design advance rate. This is the distance of tunnel face advance achieved in a 24-hour day if all systems (excavation, support installation, material handling, and project support) operate continuously without interruption throughout the entire 24-hour period. The material flow rate required to sustain the design advance rate determines the nominal or design capacity of the material handling system. Normally, a system has the ability to operate, at least for short periods, at capacities slightly greater than the design capacity. This peaking capacity of the material handling system is not considered in the evaluations in this study.

The advance rate (A) does not necessarily represent the face advance achieved in a 24-hour period. This will ususally be considerably less than A due to downtime of one or more units of the tunneling system, thus causing the excavation equipment to cease operation or to operate at reduced rates resulting in less achievement than indicated by the design capacity. For example, if an advance of 200 feet were made in a 24-hour day but the tunneling system had been nonoperative or unavailable for two of the three shifts due to repairs or other reasons, the average advance rate would be 200 feet/day; but A would be 600 feet/day assuming the system had operated at full capacity during the one shift.

The amortization base (A_b) is the length of tunnel excavation over which the capital cost of the material handling system is distributed. This is a means of expressing a useful life for the equipment since, for a given tunnel diameter, the total length of excavation determines the amount of material which must be carried by the material handling system. This is also equivalent to equipment life expressed in hours of full capacity operation.

SIDE-WHEEL DRIVE SYSTEM

The side-wheel drive system evaluated uses the same basic concepts for both horizontal transport and inclined lift. This eliminates the need for transfer equipment at the tunnel/shaft intersection. The loading/extension system is shown in Figure 4-4 and is represented in the analysis by a sliding floor, short conveyor sections, and the side-wheel drive equipment mounted on the platform.

Data is presented for both portal and deep tunnels. The results of the analysis show the system has the potential of being one of the lowest cost systems meeting the requirements of the future. The system has low installation costs, so it appears that system lengths of 10 miles or less are economically advantageous.

The material handling costs per unit length increase as the system length increases; and at a distance of 40 miles, costs are five times higher than at 10 miles, but the true optimum length cannot be determined without consideration of cost factors which were beyond the scope of this study.

Figure 15-1 shows representative results for the side-wheel drive system operating in deep tunnels using two different strategies for advancing the tunnel complex. The construction strategies studied are discussed in Chapter 14. As the tunnel diameter increases, the material handling cost per foot increases as would be expected, but at a much lower rate than the amount of material moved. An examination of the specific cost curves in Chapter 13 for this system shows rapidly decreasing costs as tonnage increases.

As the tunnel diameter increases for a constant advance rate, the tonnage will increase by a factor of 16 between a 10-foot diameter and 40-foot diameter. The influence of rapidly decreasing specific costs on system cost is the reason for costs not increasing in proportion to the muck removal rate.

For this system, advance rate variations do not affect material handling costs significantly. For a given tunnel diameter, higher advance rates increase the equipment costs, since the equipment capacity must be greater. Operating costs, however, behave differently. As the capacity of the system is increased, the specific operating costs decrease or stay almost constant. The number of hours the material handling system operates for a given length of tunnel decreases as advance rate increases, but the hourly capacity increases. As a result, system operating costs decrease in proportion to the specific operating costs as advance rate increases. Material handling cost will either increase or decrease with advance rate depending on the relative significance of operating and equipment costs.

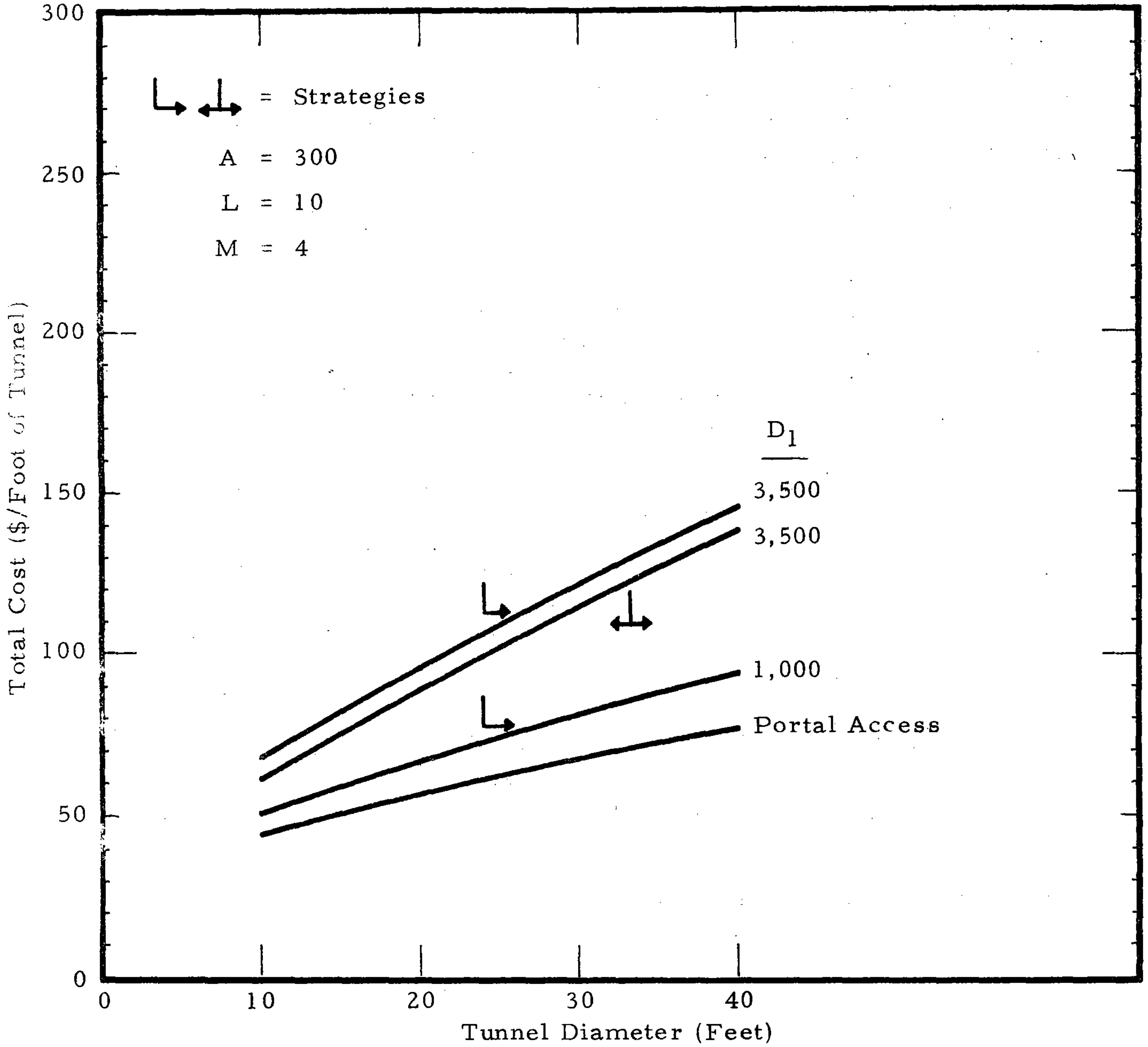


FIGURE 15-1

MATERIALS HANDLING COST
(Side-Wheel Drive System)

SIDERAIL SYSTEM

Material handling costs generated by the siderail system place this concept in a group with the pneumatic and monorail systems as the more expensive concepts considered in this study. The siderail system is expensive for horizontal transport because of the high cost of guideway ($156 per foot for installed double track) and the cost of the modules. The system could be used exclusively for vertical lift as illustrated in Figure 5-7, with economical results; but this requires a module loading device for transfer of material at the shaft station, which results in a rather complex material handling system.

Results are presented here for a siderail system used horizontally and vertically. This system in the near-face zone is illustrated in Figure 4-6. The horizontal and vertical module designs are not matched, which yields results that are probably more optimistic (i.e., lower costs) than could be attained if the designs were matched. Figure 15-2 presents data for the system at various tunnel depths. This system, like the side-wheel drive system, shows very little cost variation between 300 feet per day and higher advance rates (the differences do not exceed 5 percent).

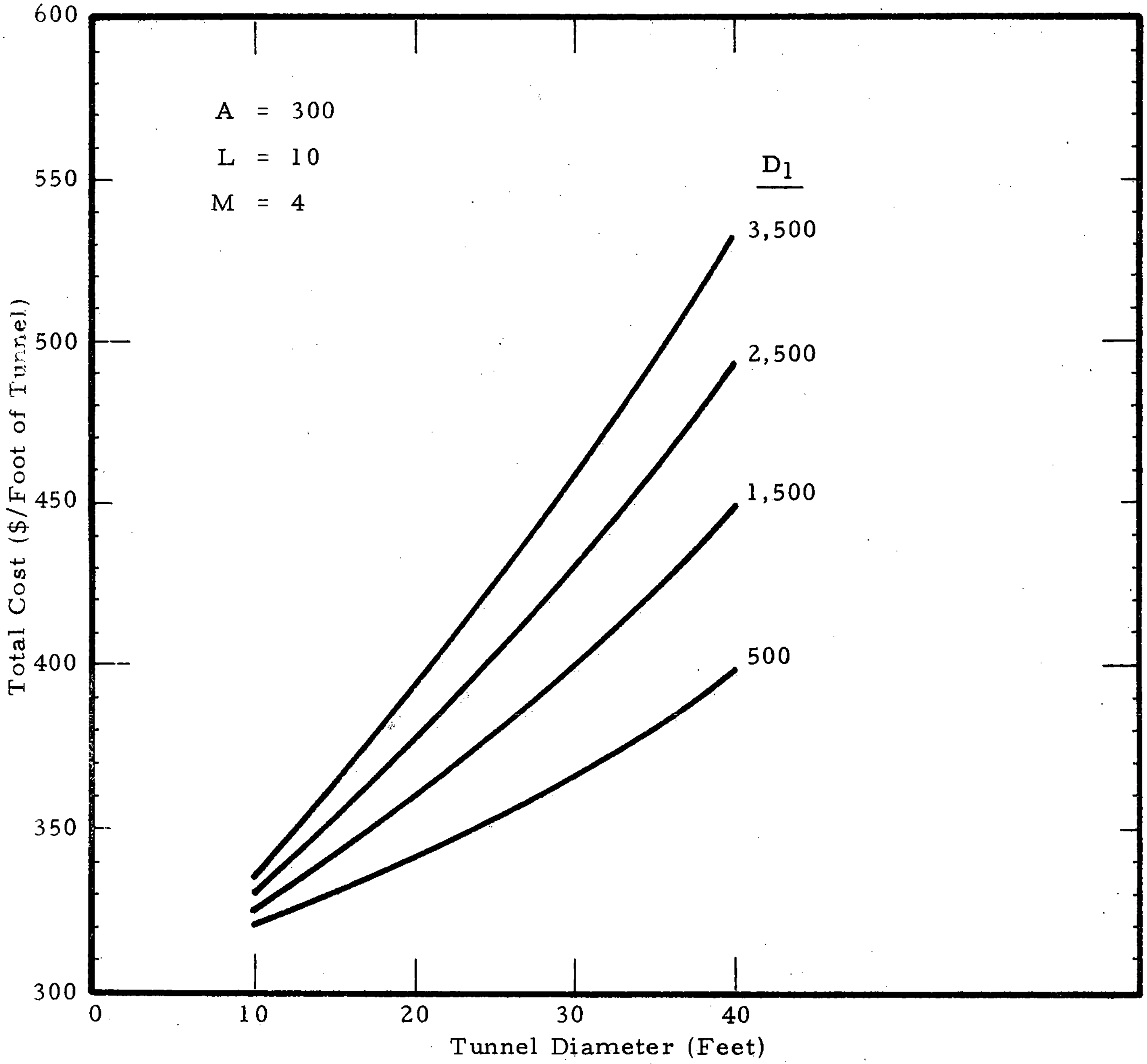


FIGURE 15-2

MATERIALS HANDLING COST
(Siderail System)

MONORAIL SYSTEM

The monorail system was combined with the hoist to form a total material handling system with both horizontal and vertical lift capability. Other system units included in the integrated system are:

- Conveyor pit (at shaft station)
- Crews for material handling at shaft station and near face
- Sliding floor
- Short conveyor sections
- Monorail extension and loading system

The system was assumed to handle both muck and incoming materials. The monorail extension and loading system shown in Figure 4-7 was assumed to be similar in cost and complexity to the siderail loading system, except for the labor function for the guideway extension which was adjusted to reflect the monorail system structure cost function as described in Appendix 3B. It was assumed that the ring segment supports and one monorail track were left behind for finishing the tunnel. This is consistent with guideway cost functions used throughout the systems analysis.

Figure 15-3 presents results of the analysis of the monorail total system. The results indicate that the monorail system suspended from full ring supports would be one of the most costly material handling systems of all those considered. This is particularly true for 30-foot and 40-foot diameter tunnels. Ten-foot diameter tunnels show costs which are very competitive. This emphasizes that the cost gradient as a function of tunnel diameter for this system is very steep. It is evident that this gradient reflects the cost of the monorail transport system, which in turn reflects the cost magnitude of the guideway support and rails. In general, the costs appear competitive for 10-foot diameter tunnels where much less supporting structure and smaller monorail beams are required.

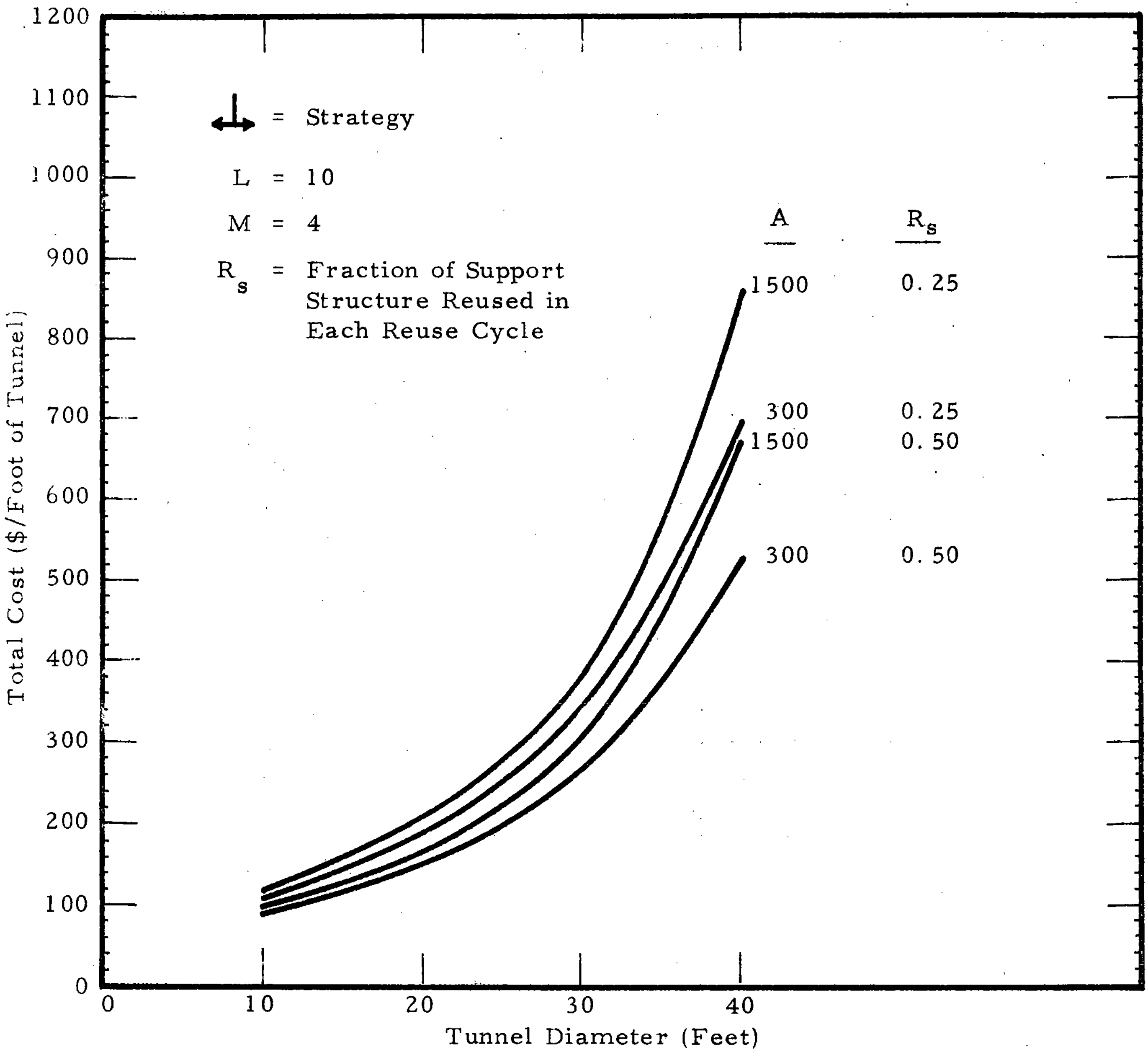


FIGURE 15-3

MATERIALS HANDLING COST
(Monorail/Hoist System)

TRUCK SYSTEM

During the study it became evident that if truck systems could be used in tunneling as they are in surface applications, they would have the potential to operate with the same cost advantages and flexibility as they do on the surface. These advantages are difficult to exploit in tunnel construction at high advance rates because several problems are encountered.

In a round tunnel at high advance rates, a roadbed is required if trucks are to operate at the speeds required to give the material transport system the capacity over long distances needed to keep pace with the advancing face. The preparation of a roadbed in a tunnel adequate for these speeds will be both difficult and costly. Figure 14-4 shows the effect on total material handling system cost of higher performance roadbeds. The basic system cost with minimum or essentially no roadbed preparation cost is compared to the system costs if roadbeds costing 10 dollars per foot and 30 dollars per foot are used. A horseshoe or vertical sidewall tunnel would require minimum or no roadbed preparation, thus providing the best conditions for using trucks.

The system analysis in Appendix 3B assumes that trucks used in tunnels would be configured to allow traffic at high speeds and simultaneously in two directions. In 10-foot diameter tunnels, the truck width (3 to 4 feet) would result in a marginally stable configuration. For tunnels of larger diameters, trucks might be used; but if speeds of 35 miles per hour are to be attained, automatic steering devices might be required.

A third problem is the necessity to rapidly sequence the vehicles in the loading zone. This must be accomplished with clock-like precision at rates of up to one vehicle per minute, which includes spotting, loading, and allowing trucks carrying incoming material to pass the muck loading stations and proceed to the unloading station. Compared with other systems the sequencing of independent rubber-tired vehicles appears more complex and less practical.

Based on the above discussion, the position taken in the analysis is that if rubber-tired vehicles are used in tunnels driven at very high advance rates, they should be considered for hauling incoming material only, using conveyors or hydraulic methods to remove muck. This dual mode concept using conveyors and trucks is shown in Figure 5-4. Cost data for a system consisting entirely of trucks is presented in Figure 15-4, which may be compared with data for the dual mode conveyor/truck system presented as part of the evaluation of conveyor systems in Figure 15-13. In large horseshoe tunnels, trucks might be an economical choice. Figure 15-5 shows how the total tunnel distances over which the cost of the truck system is amortized affects the material handling cost.

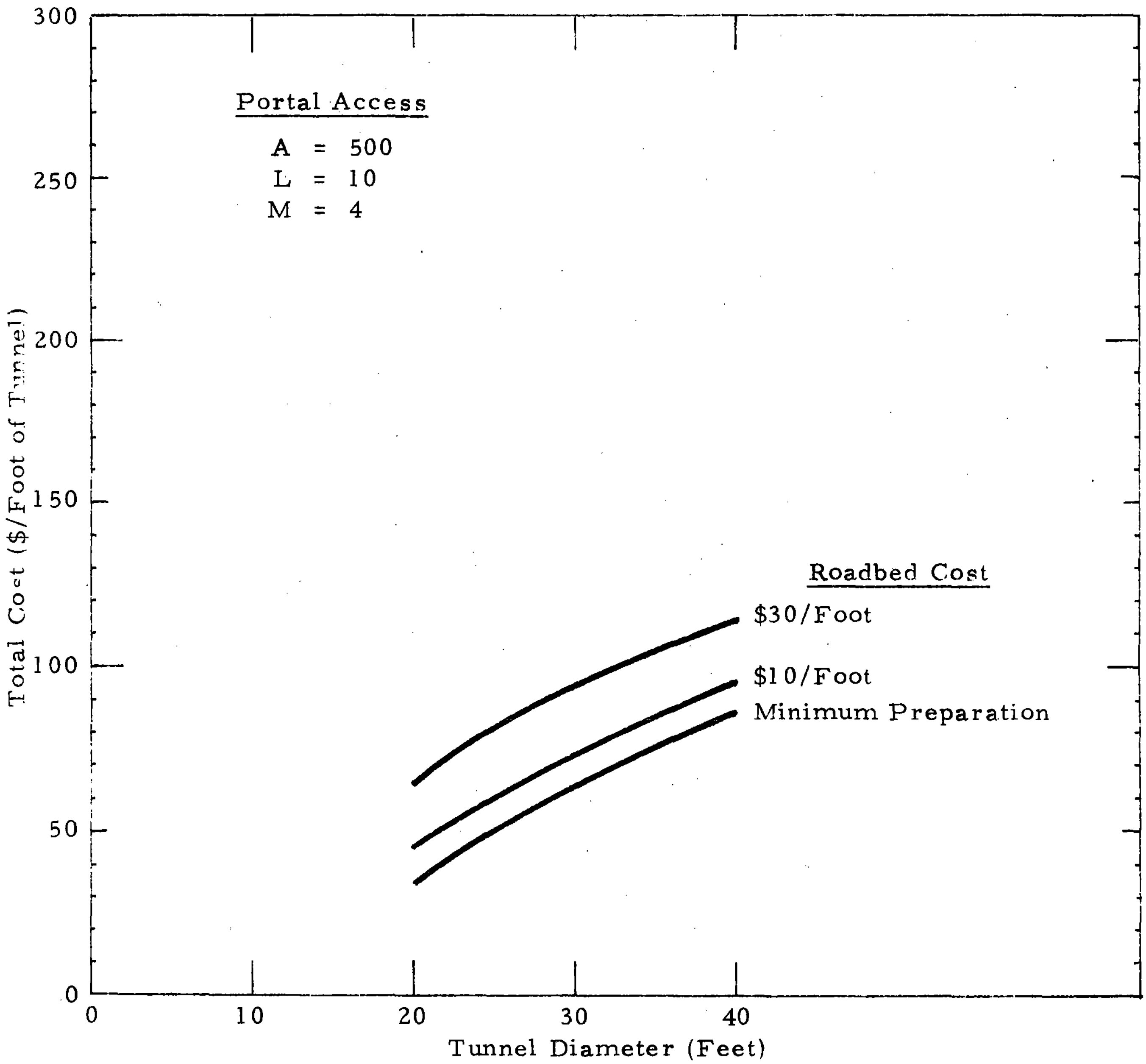


FIGURE 15-4

MATERIALS HANDLING COST
(Truck System)

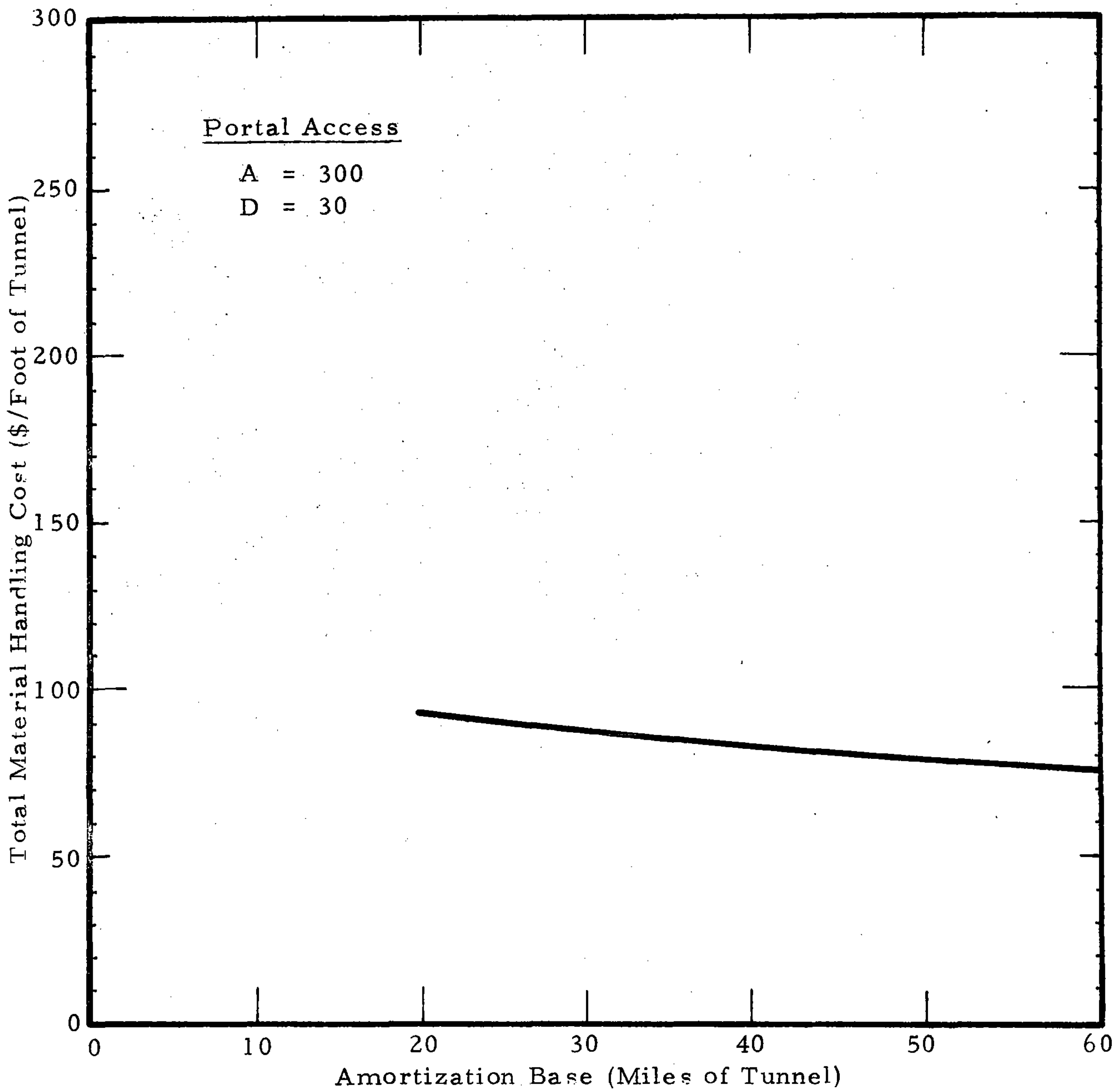


FIGURE 15-5

EFFECT OF AMORTIZATION BASE
(Truck System)

LOCOMOTIVE DRIVE SYSTEM

Locomotive driven trains on conventional rail track have been used satisfactorily for many years for material handling in tunnels. It is appropriate to compare this system with others and to determine the limits of its capacity. The results of the systems analysis for this transport mode show that high performance adaptations of the locomotive drive system are competitive under favorable conditions with the side-wheel drive and truck systems. The high performance characteristics assumed in the system analysis for the locomotive drive system are an important factor in the competitive position of this system.

For systems which require more than three locomotives, it is assumed that double tracks would be required to carry the traffic. Two muck loading stations, as indicated in Figure 4-3, are required on all locomotive drive systems. The double-track requirement complicates the problem of providing a high quality roadbed of sufficient width to provide clearance for two trains, as indicated in Figure 2-2. Muck cars are assumed to have the capability to unload rapidly (1 minute for a whole train). Incoming materials are assumed to be loaded on cars at the leading end of the inbound train so they can be uncoupled and towed to the unloading station at the near-face zone and when empty shuttled back to another train for return to the shaft or portal area.

The locomotive system is limited to very slight grades; so for deep tunnels, alternate methods must be provided for lifting muck and lowering incoming materials. The two methods analyzed are the balanced hoist with a skip for muck and a cage for incoming materials, and the cable drive concept which facilitates towing loaded muck cars up an incline and returning empties and cars loaded with construction materials.

The complete list of system units included in the analysis of the integrated locomotive drive/hoist system is:

- Muck loading system
- Short conveyor sections
- Tracklaying crew
- Material handling crews at the near face and shaft station
- Locomotive drive transport system
- Shaft station transfer pit
- Hoist system

The locomotive drive/cable drive integrated system includes the following units:

- Muck loading system
- Short conveyor sections
- Tracklaying crew
- Material handling crew at the near face
- Locomotive drive transport system
- Cable drive transport system

Locomotive Drive/Hoist System

A concept of the locomotive/hoist system at the shaft station is shown in Figure 5-1. Figure 15-6 presents the results of the analysis for comparison of the locomotive drive systems used in portal tunnels and deep tunnels. For portal tunnels where hoists are not required for vertical lift, the cost of material handling is slightly higher for the locomotive drive system than for the corresponding case for the side-wheel drive system presented in Figure 15-1. As the tunnel depth increases, material handling cost increases; and for 40-foot diameter tunnels, the material handling cost at a depth of 3,500 feet is almost double the cost for a portal access tunnel.

Figure 15-7 shows how the tunnel length over which equipment is amortized affects the material handling cost. In the example, amortizing equipment over 80 miles of tunnel instead of 40 miles of tunnel reduces material handling cost by 10 to 15 percent.

Figure 15-8 shows the results of a special case study involving parallel 10-foot diameter tunnels accessed by a single vertical shaft complex housing the hoist system. It is assumed that the tunnels will be driven in both directions from the shaft (a total of four tunnel segments). If the four segments are driven simultaneously, the hoist capacity is required to be four times the capacity that is required if the tunnel segments are driven in sequence. A cost reduction is shown for tunnels driven in sequence. Figure 15-8 also shows the effect of extremely high advance rates on material handling cost. The costs for various advance rates between 300 and 11,000 feet per day are fairly constant but appear to show a slight increase for very high rates.

Figure 15-9 shows the effect of tunnel segment length on material handling cost using a constant tunnel length (40 miles) for amortizing equipment. The amortization base is maintained constant by increasing the number of use cycles (M) as the tunnel segment length (L) decreases so the product (M x L) remains constant. The results show lower costs for

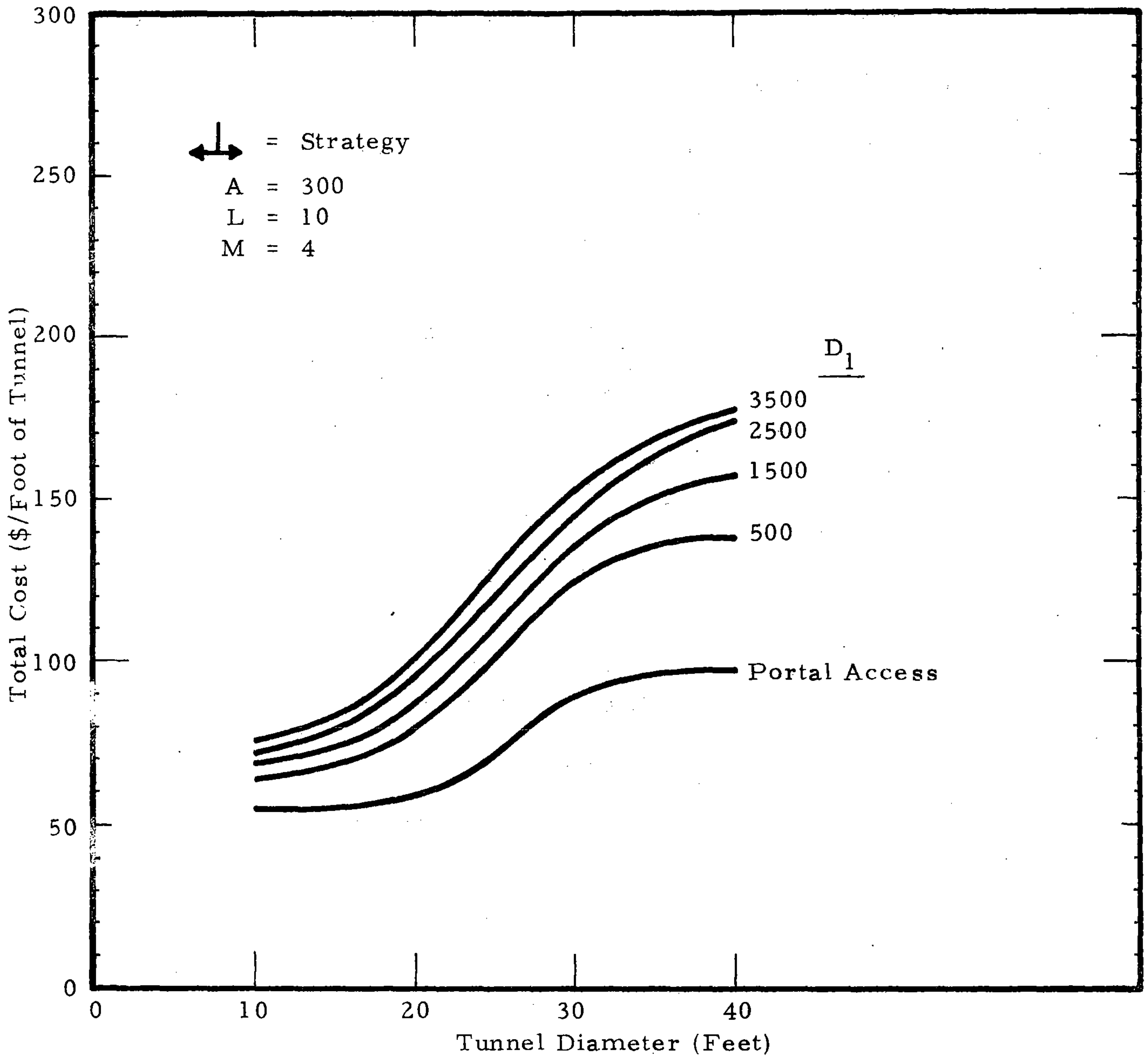


FIGURE 15-6

MATERIALS HANDLING COST
(Locomotive Drive/Hoist System)

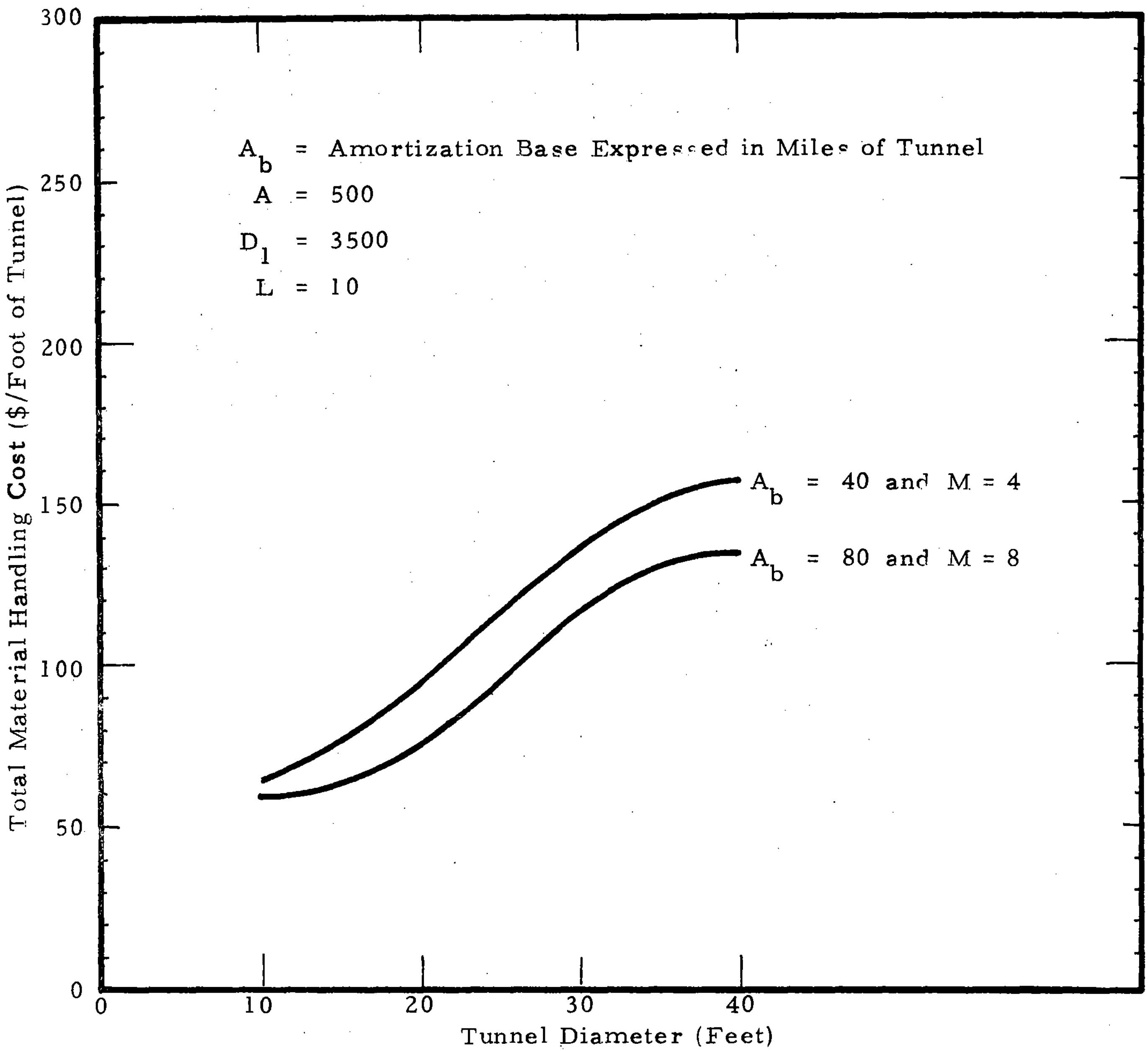


FIGURE 15-7

EFFECT OF AMORTIZATION BASE
(Locomotive Drive/Hoist System)

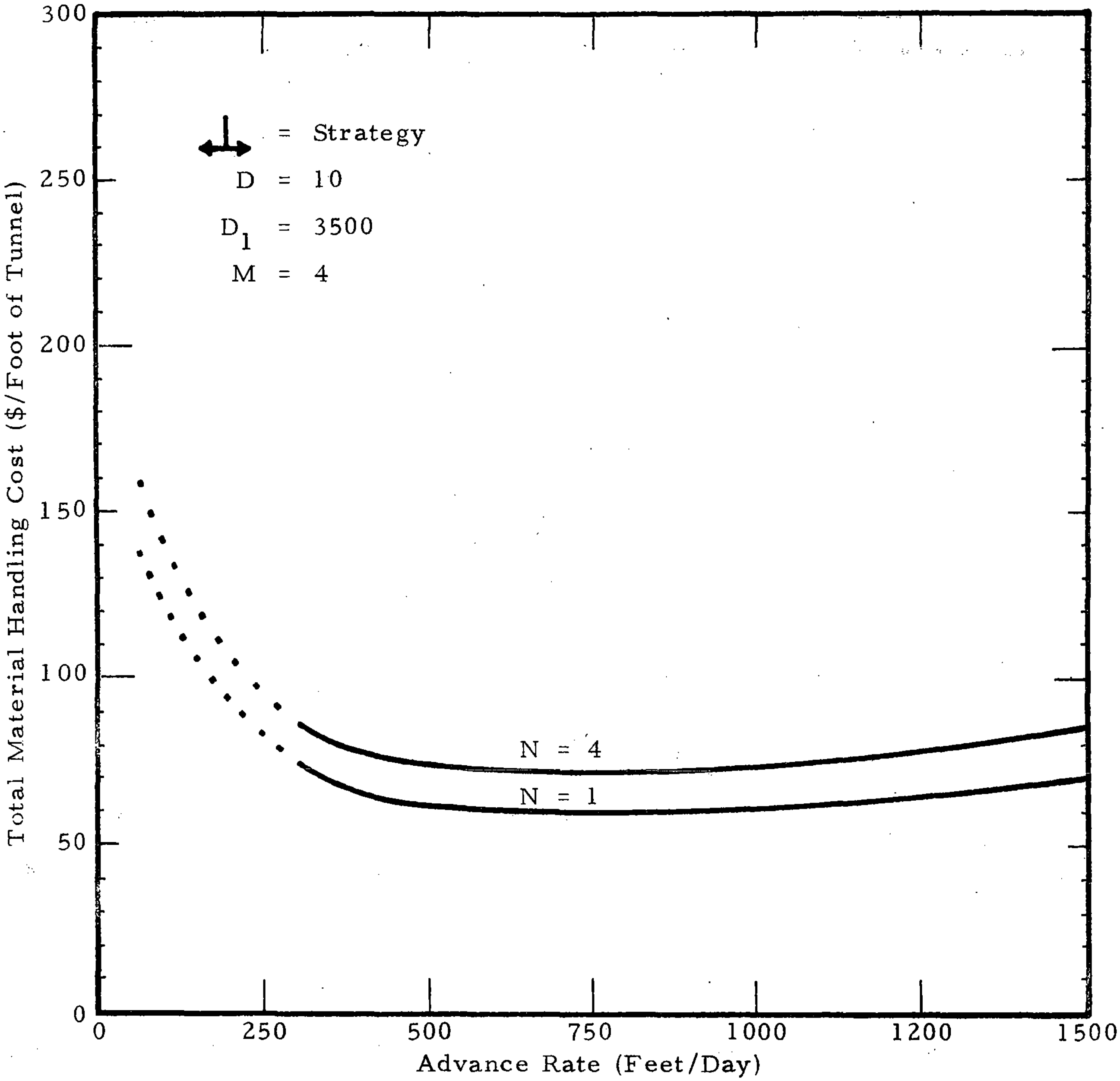


FIGURE 15-8

EFFECT OF SIMULTANEOUS TUNNELS DRIVING
(Locomotive Drive/Hoist System)

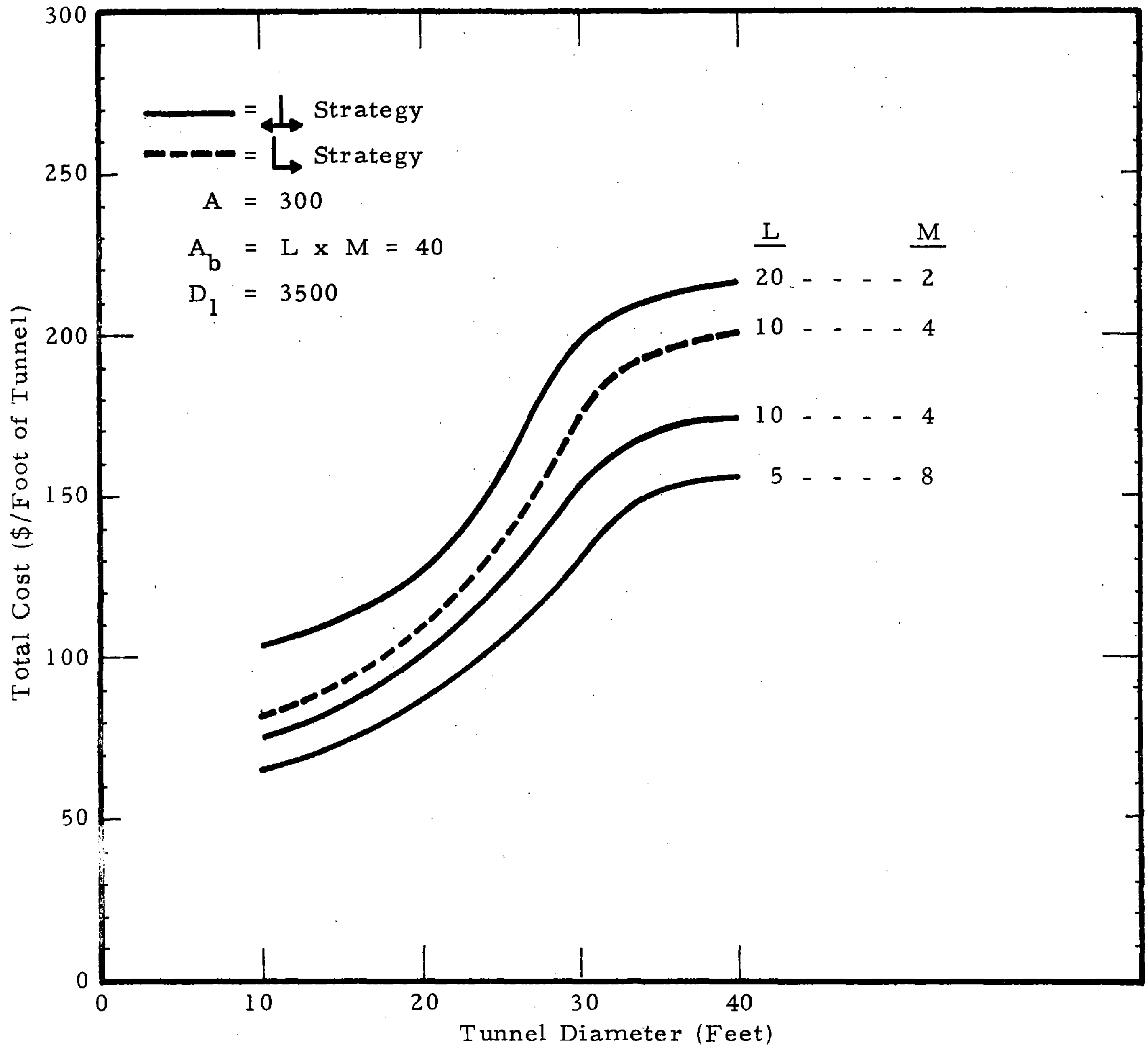


FIGURE 15-9

EFFECT OF TUNNEL SEGMENT LENGTH
(Locomotive Drive/Hoist System)

shorter length runs, but it is cautioned that any costs which remain fixed for various tunnel lengths (such as shaft costs) will tend to increase the distance over which material can be transported economically. Shaft costs (and many other costs which are fixed with each installation) are not included in this analysis.

Locomotive Drive/Cable Drive System

Results for the integrated system combining locomotive driven trains for horizontal transport with the cable towing arrangement for inclined lift are presented here. Inclined shafts, as shown in Figure 5-2, are required for this arrangement; but if inclined shafts are available and the cable drive mechanism proves to be feasible, many of the shortcomings of both trains and hoists can be overcome. First, trains towed by locomotives have severe grade restrictions; the cable drives overcome this to some extent. Secondly, using the hoist for vertical lift requires costly transfer stations for both muck and incoming materials. If a means can be provided to tow the cars of the train to the surface and return them, as the cable drive mechanism is conceived to do, then the muck need not be transferred from the car until it reaches the disposal site; and incoming material is not transferred until it is loaded. Figure 15-10 shows results obtained for this system at different tunnel depths. The results indicate a potential material handling cost reduction for this method compared with the locomotive drive/hoist concept of Figure 15-6.

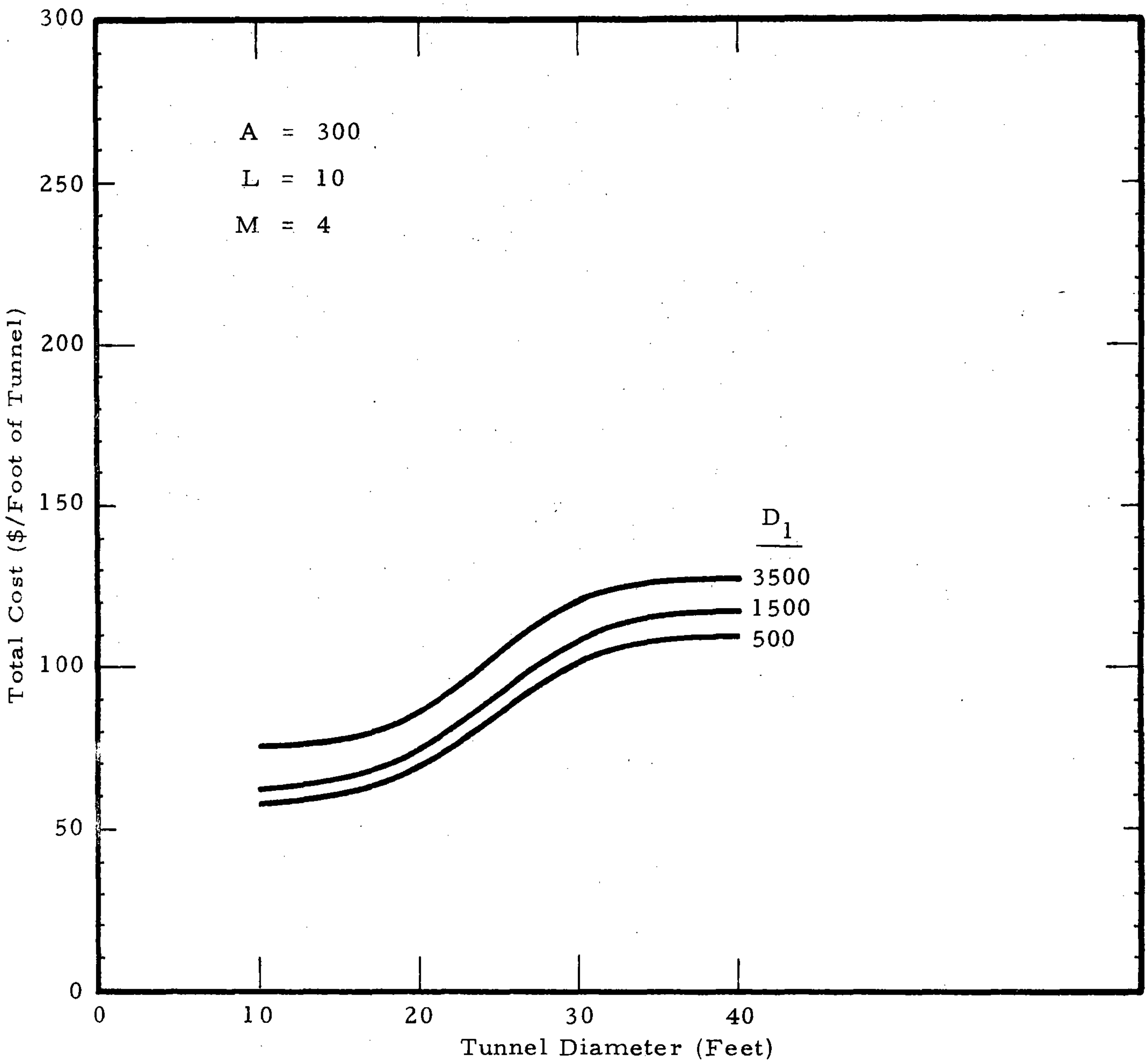


FIGURE 15-10

MATERIALS HANDLING COST
(Locomotive Drive/Cable Drive System)

CONVEYOR SYSTEMS

Two system combinations incorporating conveyors were studied. In each integrated system concept, the conveyor handles muck only and a separate means is provided for transporting incoming material. A conveyor/hoist/locomotive drive combination is suitable where a vertical shaft is used as shown in Figure 5-3. With this combination the muck is transported by the conveyor and a skip hoist while incoming material is handled by a hoist cage and the locomotive drive system. If an inclined shaft is available, a representative system combination might consist of conveyors for horizontal transport and inclined lift of muck, with trucks as a logical choice for incoming material as shown in Figure 5-4.

Figure 15-11 presents data for the conveyor/hoist/locomotive drive integrated system. Units of the system are:

- Horizontal conveyors
- Sliding floor
- Conveyor/hoist transfer
- Hoist system
- Locomotive drive system
- Crew for material handling at shaft station
- Crew for material handling at near face
- Track extension crew.

If the results shown on Figure 15-11 are compared with those on Figures 15-1, 15-4, or 15-6 for similar conditions, it is evident that the multi-mode conveyor system is more costly. Operationally, a system utilizing conveyors might be less complicated, since muck and incoming materials need not be sequenced on the same system.

For this system combination, costs vary to ±15 percent as advance rates are varied from 300 to 1,500 feet per day. For 10-foot diameter tunnels, costs tend to decrease as advance rates increase. For 40-foot tunnels, however, costs tend to increase as advance rates increase. Figure 15-12 presents results for various lengths over which the material handling equipment costs are amortized.

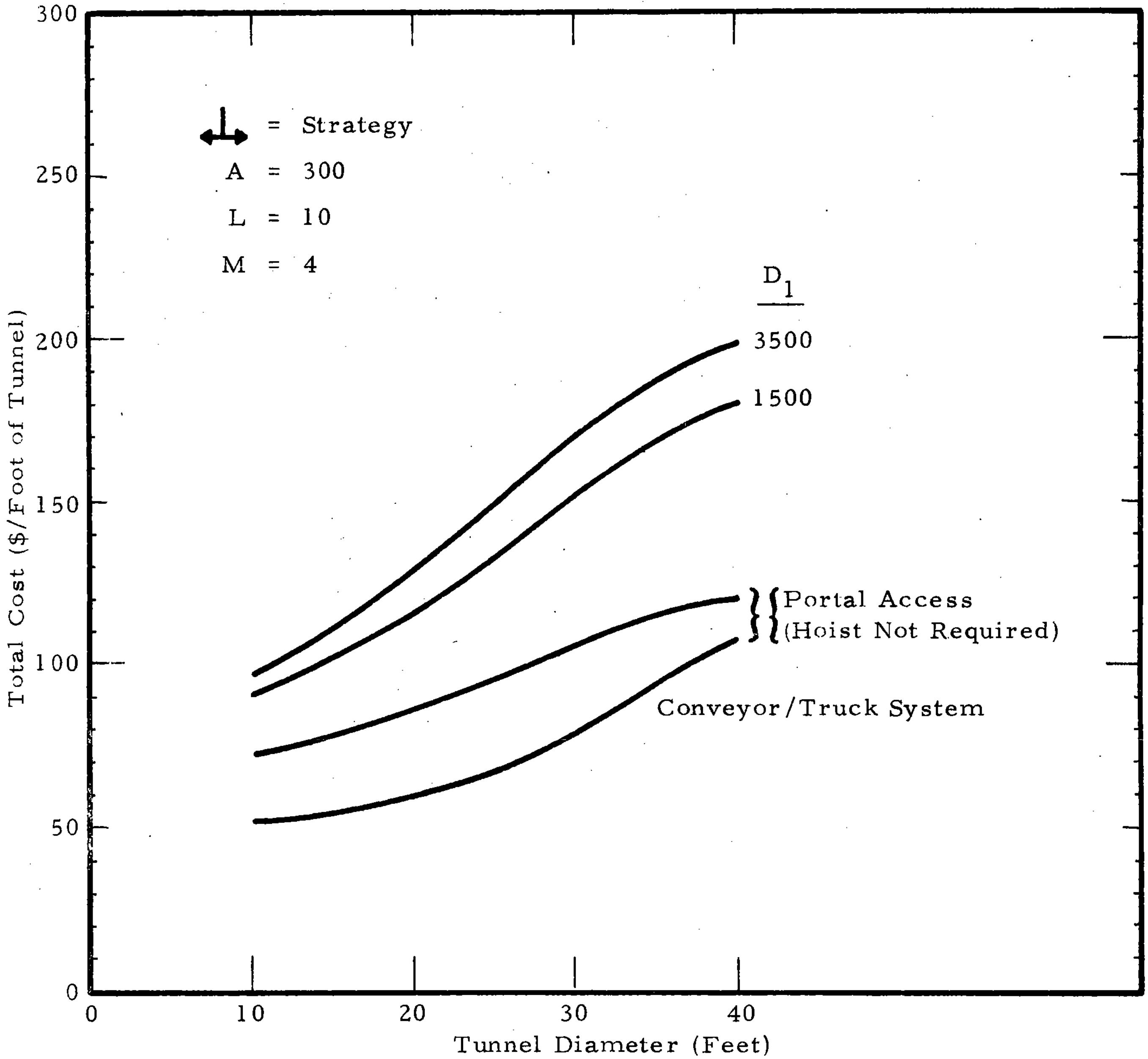


FIGURE 15-11

MATERIALS HANDLING COST
(Conveyor/Hoist/Locomotive Drive System)

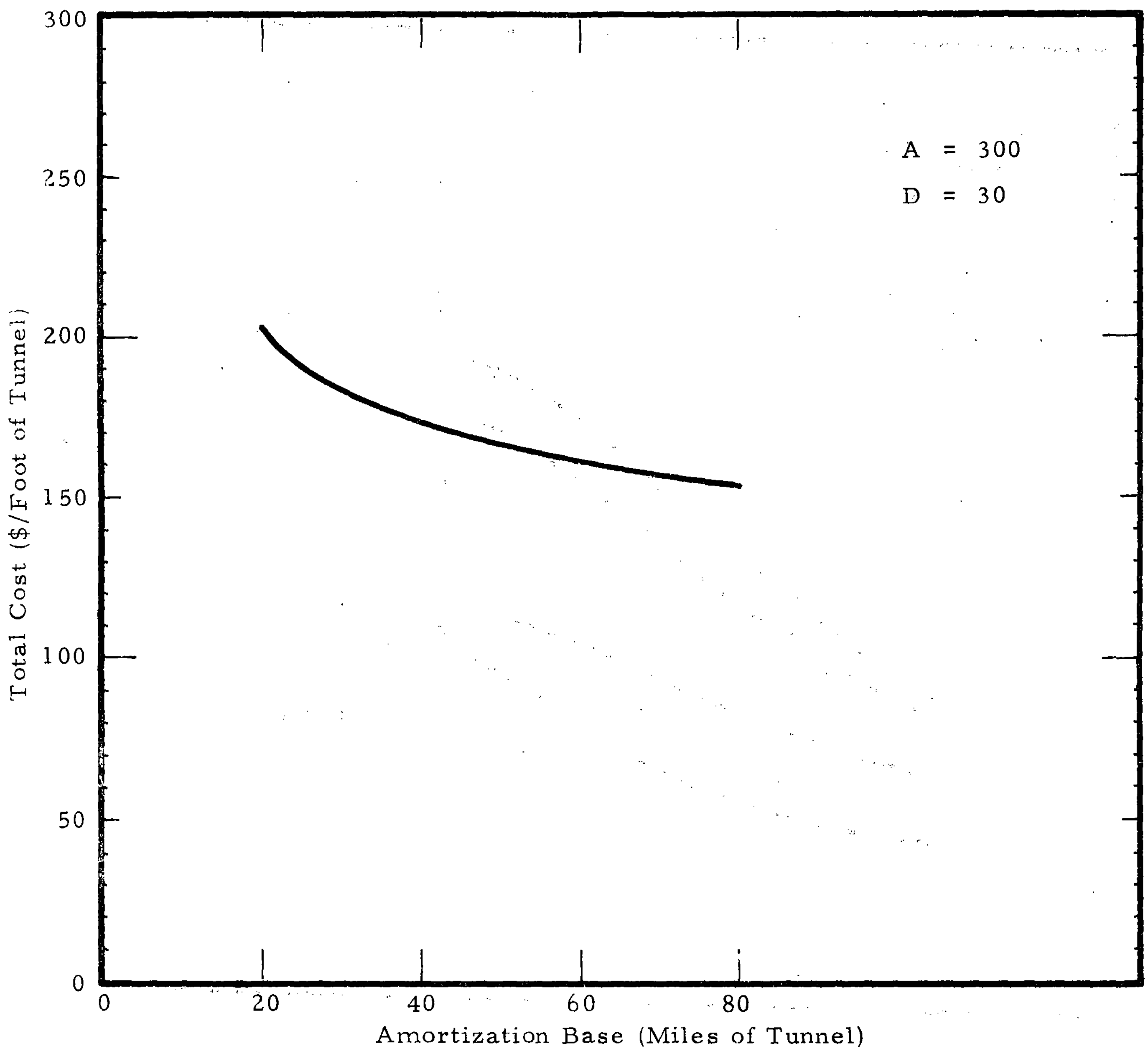


FIGURE 15-12

EFFECT OF AMORTIZATION BASE
(Conveyor/Hoist/Locomotive Drive System)

For this case study it was assumed that the muck did not require crushing before being transported on the conveyor. Crushing, which might be required if conventional excavation or flame disintegration of rock is used, would add significantly to the cost, particularly for large diameter tunnels. Most of the advanced boring machines appear to have the potential to control the size of the muck particles created by the rock breaking process, so for this case it seemed reasonable to assume that muck particles are no larger than one-fourth the width of the conveyor belt which is accepted practice for belt conveyance. For example, a 24-inch belt and 6-inch particle for a 10-foot diameter tunnel would be typical.

If inclined shafts are available, conveyors may be used to lift muck to the surface. This has the advantage of eliminating the need for major transfer equipment at the shaft and simplifying operations. Trucks are selected for transporting incoming material in this concept. The cable drive system is included at the inclined shaft to aid the trucks in their climb to the surface. Figure 15-13 presents the results of analysis for this system combination. In this case study, the ratio of incoming material to muck removed (K, equivalent tons in/ton out) is varied from the maximum value (0.28) to 0.04 which is considered a practical minimum. Material handling costs are reduced accordingly, particularly for large tunnels at high advance rates. Figure 15-13 also shows the effect of advance rate variation on material handling cost for this system combination.

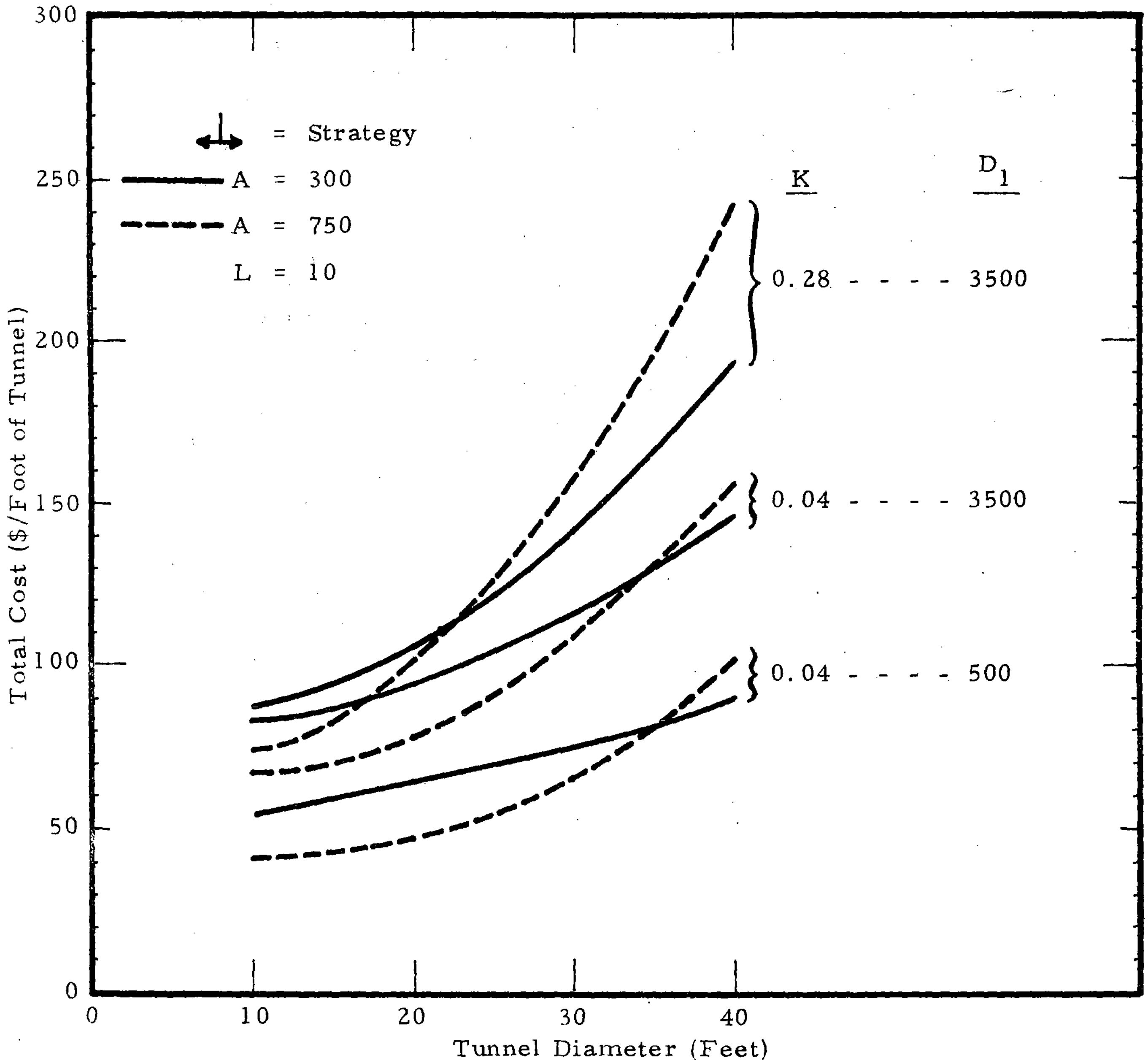


FIGURE 15-13

MATERIALS HANDLING COST
(Conveyor/Truck/Cable Drive System)

HYDRAULIC SYSTEMS

The hydraulic system configuration analyzed is described in more detail in Appendix 3B and illustrated in Figures 3-6, 5-5, and 5-6. Unlike the conveyor, the hydraulic slurry system can be used to transport muck vertically as well as horizontally; and if the muck is transported horizontally in a slurry, then it is logical to lift it hydraulically. Incoming material is transported by hoist and locomotive drive systems in the case study. The complete list of units included in the system is:

- Short conveyors
- Sliding floor
- Vertical hydraulic system
- Horizontal hydraulic system
- Crushing and hydraulic system extension (crushing optional)
- Locomotive drive system
- Hoist system
- Crews for material handling at near-face and shaft station.

Crushing is necessary to provide a high percentage of fines in the slurry and to limit the size of particles to that which can be pumped through reciprocating pumps. The case study assumes that single-pass crushing will be sufficient to create the necessary fines. In addition, another case was run without crushing to identify the cost impact of crushing, which appears to be from 25 to 30 percent of costs chargeable to material handling.

The results are shown on Figure 15-14 for the hydraulic/locomotive drive/hoist system combination. It is again observed, as it was for the multi-mode conveyor system, that system combinations requiring separate modes for the in-flow and out-flow of materials are more costly than single mode systems which have the capability to transport materials in both directions. If the results shown on Figure 15-14 are compared with results shown on Figures 15-1, 15-4, or 15-6 for the same tunnel configuration, this is evident. The cost differences between conveyors and hydraulic systems are not great. More study would be required to provide a precise cost basis for choosing between the two. Figure 15-14 also indicates that cost does not vary more than 10 percent as advance rates increase.

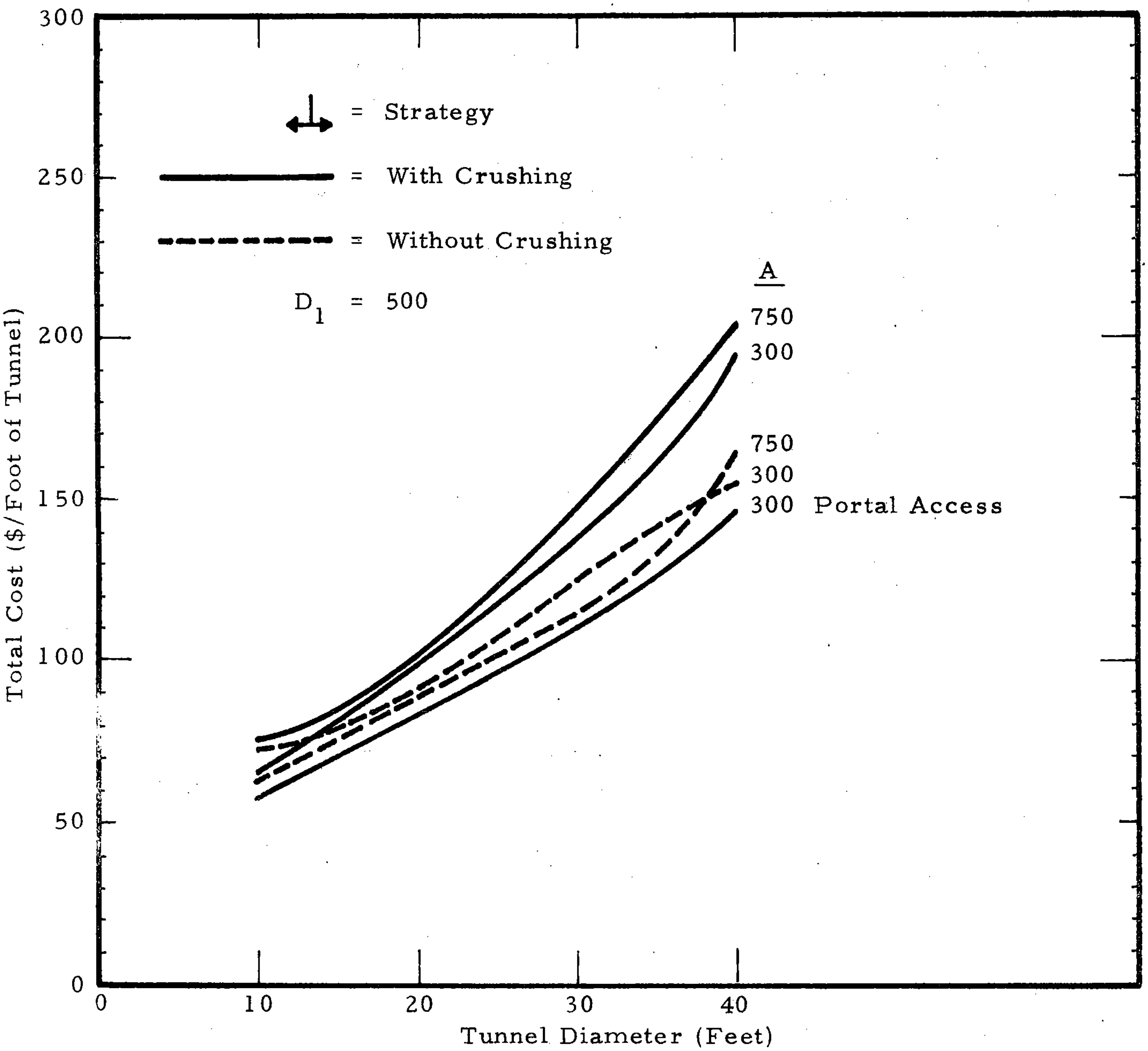


FIGURE 15-14

MATERIALS HANDLING COST
(Hydraulic/Locomotive Drive/Hoist System)

PNEUMATIC SYSTEM

Based on the data for pneumatic systems presented in Appendix 3B, it is evident that pneumatic systems are uneconomical when used to transport muck horizontally over long distances. For vertical lift heights of 1,000 feet (and perhaps higher), pneumatic systems may be a competitive alternative. The application concept which meets the constraints and advantages of the pneumatic system consists of using exploratory holes (assuming they have been drilled every 1/4 mile) as the vertical path by which muck is removed from the tunnel as illustrated in Figure 3-9. The horizontal system is thus limited in length to slightly more than 1/4 mile, and this system could be either pneumatic or a conveyor towed behind the excavation machine.

For tonnage flow rates up to 300 tons per hour the muck could be removed through a cased 14-inch diameter hole for a fraction of the cost which accompany other systems. The system would be adequate for 10-foot diameter tunnels at high advance rates, and for 20-foot diameter tunnels up to 300 feet per day. Muck would be delivered to the surface at 1/4-mile intervals. This might be undesirable in some cases. The use of pneumatics does present a unique approach with the potential for reducing muck-removal costs in tunnels if used in this configuration.

AVAILABILITY EFFECTS

The tunneling process envisioned in the analysis is a continuous one, that is, excavation, muck removal, liner installation, and other functions proceed simultaneously. Present-day tunnel construction is often carried out under cyclic conditions with various operations performed in series rather than simultaneously. In order to achieve extremely high advance rates, simultaneous operation of the various systems appears to be an absolute requirement. If any critical system is not operable for any reason, it will probably bring the advancing excavation to a halt.

Strictly speaking, the availability of the tunneling system is defined as the ratio

$$\underline{A} = \frac{x}{x + y}$$

where

x = time operating at design advance rate (A), and

y = down time during scheduled operating shifts.

It is not too misleading, however, to think of the availability ratio as a measure of operational efficiency, with a perfect continuous system obtaining a value of $\underline{A} = 1.0$. Using this concept, the design advance rate can be related to the average daily advance rate through the availability term

$$\underline{A} = \frac{\text{Average daily advance rate (feet/day)}}{\text{Design advance rate (feet/day)}} .$$

The total material handling system availability is computed by the factor πA_6 in the integrated system model. The individual system availability terms are summarized in Table 3A-23. The usability of the material handling system is affected also by the availability of all other units of the total tunneling system since malfunction of any one of these units can cause the material handling system to be out of use. The availability of the excavation machinery and all other units critical to operation of the total tunneling system is represented by the excavation system availability term (A_7). The overall tunneling system availability ($\underline{A}$) which is equal to the material handling system usability is the product of the material handling system availability (πA_6) and the excavation system availability (A_7).

In the basic case presented in all the results of the previous analyses, an excavation system availability (A_7) of 0.7 has been used to represent conditions in the 1975 to 1980 time frame. This assumes that much progress will be made in the design and operation of the excavation machinery and all other critical units of the excavation system. Present-day mechanical excavators experience availabilities less than 0.8 under ideal conditions; and typically, values of A_7 for the total excavation system are 0.2 to 0.3.

The results of the analyses have shown that operating cost is a major contributor to material handling system cost. As the overall tunnel construction system degrades (i.e., the availability decreases) the time that the operating and maintenance crews must be on the job increases and cost per foot of tunnel increases accordingly.

An analysis series was made using the hydraulic/locomotive drive/hoist system combination as the example system. The availability term (A_7) was varied and the effect on material handling cost was observed. Figure 15-15 presents the results of this series. The cost increases as excavation system availability decreases. A general conclusion is that lower tunneling costs will accompany a tunneling system which attains a high degree of availability, that is, a high degree of operational continuity.

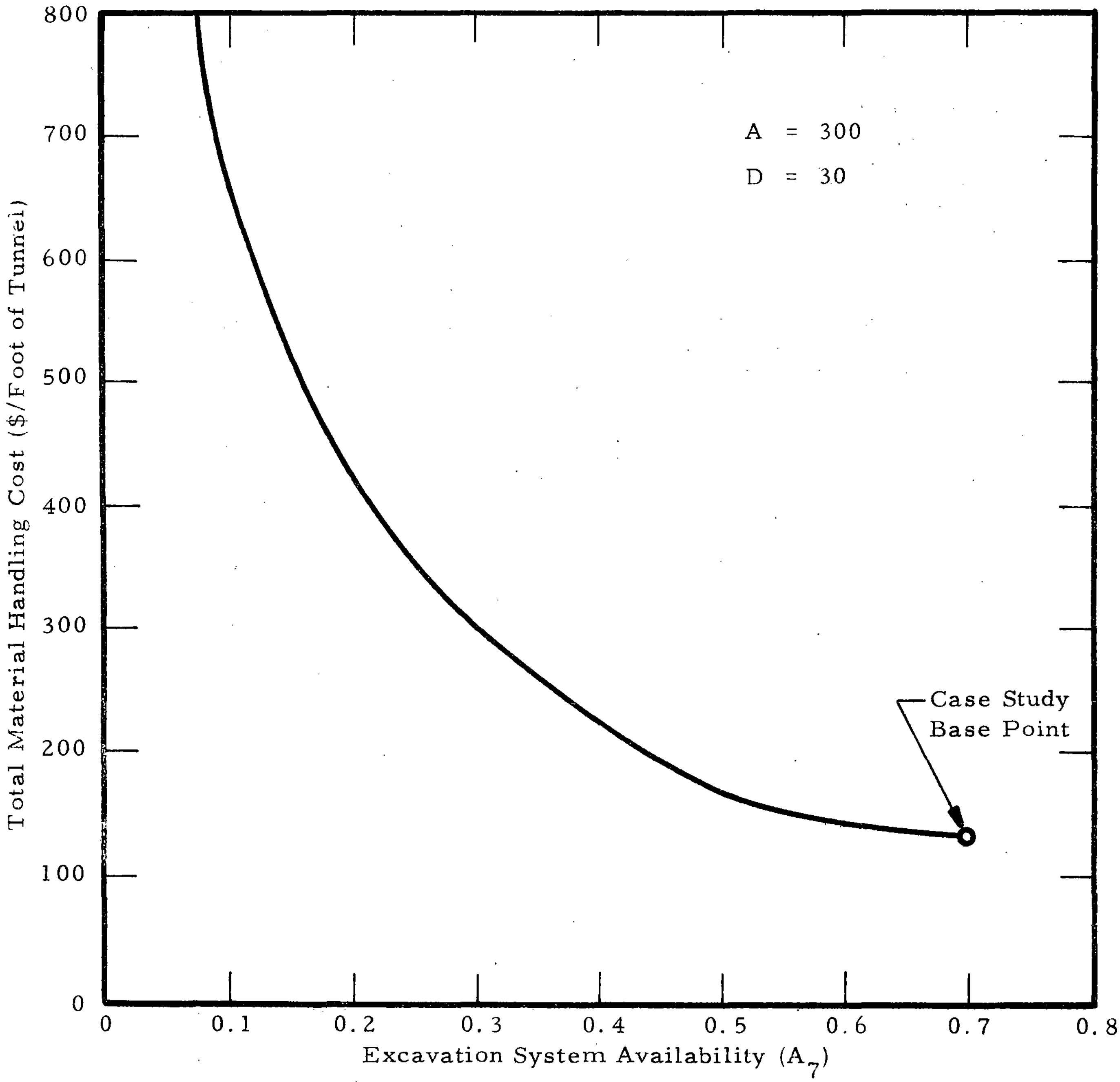


FIGURE 15-15

EFFECT OF EXCAVATION SYSTEM AVAILABILITY
(Hydraulic/Locomotive Drive/Hoist System)

EFFECT OF CONSTRUCTION STRATEGY

In most cases, the data presented in the preceding systems analyses were for the construction strategy (←┴→), in which two tunnel segments are advanced sequentially in opposite directions away from a shaft station. Separate studies were made to compare the material handling costs using the alternate strategy (└→), in which a single segment is advanced away from the shaft station. The difference between these two construction sequences which are represented in the analysis are:

- The number of tunnel segments supported by a single shaft varies.
- Using strategy (←┴→) two segments feed each shaft; only one segment feeds each shaft for strategy (└→).
- The lifting equipment is moved from shaft to shaft as needed. Strategy (└→) requires twice as many moves of lift equipment as required by (←┴→) for the same total length of tunnel.
- The loading and horizontal transport equipment moves are considered. Since the construction strategy (←┴→) requires a change in direction between each segment and removal from underground each time a new shaft is used (every other segment), the mobilization effort for horizontal transport equipment is greater for strategy (←┴→) than for strategy (└→).

Factors such as the number of vertical or inclined shafts required, relative construction costs of shafts, and mobilization costs of non-material handling equipment were not included in the analysis.

Based only on material handling costs, the result of the above comparison indicates that the construction strategy (└→) will be 10 to 20 percent more costly than the strategy (←┴→), as illustrated in Figure 15-1 for the Side-Wheel system and in Figure 15-9 for the Locomotive Drive/ Hoist system. This is due to more effective utilization of shaft installations in the latter case. If shaft costs and other construction costs are included, they would probably make the cost difference between construction sequences greater than indicated here.

EFFECT OF TUNNEL SHAPE

In general, for systems incorporating a truck or conventional rail mode of transport, material handling costs will be less in horseshoe and vertical sidewall tunnels than in round tunnels. The roadway or guideway base preparation costs should be less for a horseshoe-shaped tunnel because a relatively flat, easily stabilized surface on the bottom of the tunnel is available. In addition, if the horseshoe-shape provides more efficient utilization of the cross-sectional area than provided by the round shape for the intended application (which is the case for most conventional transportation systems), a smaller cross-sectional area can be used, resulting in less material transported per foot of tunnel. This will result in a corresponding reduction in material handling cost for a given tunnel length.

The results obtained from the integrated systems analyses presented in this chapter may be adjusted to fit the horseshoe or vertical sidewall cases by finding the equivalent circular diameter of the horseshoe-shaped case with equal cross-sectional area and reading the graphs accordingly. Adjustments can also be made for roadway preparation costs above the nominal roadway cost included in the analyses. This adjustment is illustrated in Figure 15-4 for the truck system.

PEAK LOAD EFFECTS

In the preceding analyses, the design capacity of the material handling system is determined by the design advance rate, A. The actual maximum or peak capacity of material handling systems (particularly continuous flow systems such as conveyors and pipelines) is usually only slightly greater than the nominal or design capacity.

Excavation equipment with the same design capacity (that is, design production rate matching the material handling system design capacity) will advance the tunnel face at rates varying widely around the design rate due to the differences in ground conditions encountered. A corresponding variation in material flow requirements will occur. This is illustrated in Figure 15-16.

If the material handling system is to remove muck and provide construction materials at rates sufficient to meet the material flow requirements above the requirement established by the design advance rate (during the peak production periods), a material handling system must be provided with capacity larger than that established by the design advance rate. This imposes a penalty on both operating and equipment costs for operating rates up to the design rate. The decision regarding the amount of

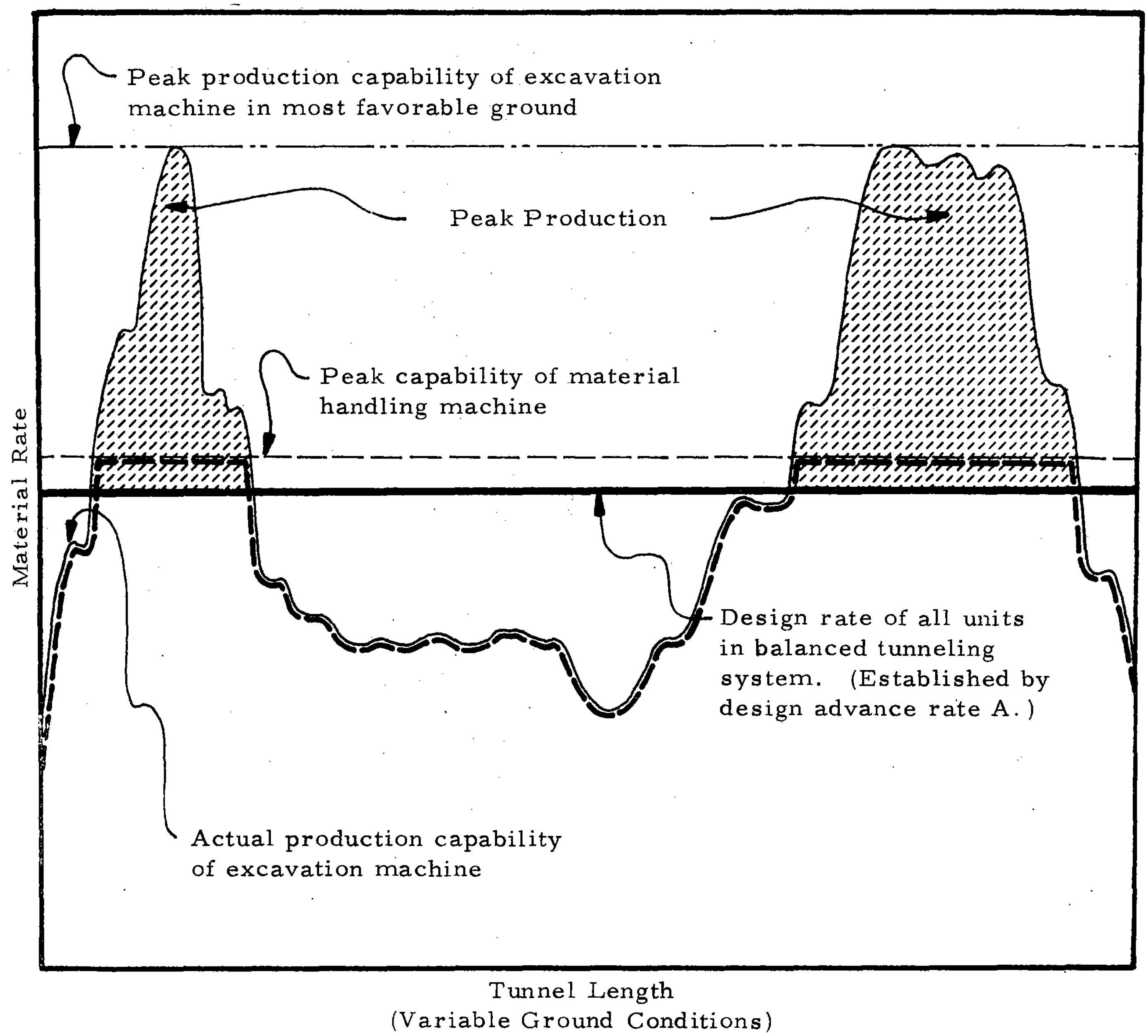


FIGURE 15-16

EQUIPMENT PEAKING CHARACTERISTICS

excess capacity to provide in the material handling system would be determined by the frequency and duration of the periods of peak production anticipated for the tunneling project. The cost of excess equipment must be balanced against the penalties incurred if the capability is not provided. If peaks in advance rate are rare, it may be prudent to limit the overall advance rate to the material handling system design advance rate, or the existing capability of the material handling system if it happens to be greater.

The appropriate costs for material handling systems with the capability to follow a peak production rate are obtained from the results in this chapter by computing the equivalent tunnel diameter necessary to generate muck at the peak rate and reading the cost from the curves. The use of an increased value of A equivalent to the peak production rate will imply that the tunnel is constructed in less overall time, and will give erroneous results. The material handling costs including an allowance for the added peak capability can be read from the data presented. The cost per foot of tunnel does not increase more than 30 percent for cases of interest.

Unitized transport modes such as the locomotive drive, truck, siderail, and side-wheel drive systems already have the capability to sustain higher than design loads for all system lengths less than the maximum segment length for which the system is designed. The system equipment (trains, trucks, or modules) is available but not required until the maximum system length is reached. When the segment is one-half its maximum length, enough equipment is available to handle about double the flow capacity, if standby operators are available and the additional traffic and reduced loading cycle can be tolerated for the peak period. Hydraulic, pneumatic, and conveyor systems have constant peak capacities regardless of system length.

APPENDIX 3A

COST ELEMENT DESCRIPTIONS

To develop meaningful comparisons of the various transport modes under conditions presented by particular tunneling projects, it is necessary to consider costs for all life-cycle phases of the proposed transport system. This should include costs associated with the development and engineering of the system to take into account the relative stage of development of the particular system. All other preoperational costs also should be included such as equipment acquisition cost, mobilization, setup, training and shakedown. Operating cost including personnel, energy, and parts and supplies is included. However, in all cases except vertical or inclined transport and operation of conveyors, the energy cost and cost of repair parts represent a small to insignificant portion of the total cost. Therefore, in most cases the labor cost is assumed to represent the operating cost.

The life cycle cost elements are identified as

C_1 = Operating cost

C_2 = Equipment cost

C_3 = Energy cost

C_4 = Setup cost

C_5 = Mobilization cost

C_6 = Development and Engineering cost

C_7 = Training and Shakedown cost

C_8 = Salvage or Disposal value

C_9 = Spares to Maintain System

To develop cost estimating relationships for operating cost, equipment cost, and energy cost, it is necessary to divide the system operation into phases such as horizontal transport, vertical or inclined transport, intermode transfer, and system loading and extension.

To determine costs for horizontal, vertical, or inclined transport, cost/performance data from Appendix 3B for various advance rates and tunnel diameters are "curve fit" to provide cost estimating relationships, or discrete values at parametric points are used as constants in the cost estimating relationships to determine operating costs and equipment costs for particular combinations of advance rate and tunnel diameter.

HORIZONTAL TRANSPORT

Modes of transport appropriate to long distance horizontal conveyance of materials are discussed in Chapters 3 and 4. The systems selected include the locomotive drive and side-wheel drive conventional rail systems, the siderail system, rubber-tired trucks, conveyors, monorail, and hydraulic pipelines. Track, train, and car configurations selected to meet the requirements for each tunnel diameter and advance rate for locomotive drive systems are summarized in Table 3A-1.

Cost estimating relationships derived from data developed in Appendix 3B for the horizontal transport systems are summarized in Table 3A-2. Except for conveyors, energy cost (C_3) is included in the operating costs. For conveyors, horsepower-per-mile values are calculated from equations in Appendix 3B and multiplied by electrical energy cost. Additional cost data used in the analysis of specific systems are summarized in Tables 3A-3 through 3A-6 for various tunnel diameters and advance rates.

In the analysis of the siderail systems, the module-carrying capacity has been adjusted upward from current designs (approximately 1 cubic yard) to accommodate larger material flow rates. One-cubic-yard modules were assumed for a 10-foot diameter tunnel, two cubic yards for a 20-foot diameter, three cubic yards for a 30-foot diameter, and four cubic yards for a 40-foot diameter.

For the truck system a maximum speed of 35 miles per hour is assumed. No road preparation costs are included. This cost could be significant in a round tunnel.

TABLE 3A-1

TRACK, TRAIN, AND CAR CONFIGURATIONS FOR LOCOMOTIVE DRIVE SYSTEMS

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	2-5-12	2-8-25	6-8-12	4-5-50
500	2-8-12	2-8-50	4-8-25	4-8-50
	ONE TRACK		TWO TRACKS	
750	2-5-25	6-8-12	6-8-25	4-11-50
1,500	Note (2)	6-8-25	6-8-50	6-14-50

KEY: 4-8-25

- 4 = Number of Trains
- 8 = Number of Cars Each Train
- 25 = Locomotive Weight (Tons) Also Car Capacity

NOTES:

1. One extra train provided each system for operating slack.
2. This case not feasible with locomotive drive system.
3. Ten-foot diameter cases for all advance rates and 20-foot diameter cases with 300 and 500 foot-per-day advance rates use single track with passing zones; all others use double track.

TABLE 3A-2

COST ESTIMATING RELATIONSHIPS FOR HORIZONTAL TRANSPORT

Transport Mode	Reference Figure	Cost Estimating Relationship	
		Operating Cost (C_1) (Dollars/Hour)	Equipment Cost (C_2) (Dollars)
Locomotive Drive	4-3	$C_1 = C_0 \times T \times L/2$ See Table 3A-3a for C_0	$C_2 = C_e \times T \times L$ See Table 3A-3b for C_e
Side-Wheel Drive	4-4	$C_1 = (1.79 \times T^{-0.705})T \times L/2$	$C_2 = (21,951 \times T^{-0.621})T \times L$
Siderail	4-6	$C_1 = (0.01526T + 17.22)L/2$	$C_2 = (136.9T + 24,576)L$
Trucks (35 miles/hour)	5-4	$C_1 = C_0 \times T \times L/2$ See Table 3A-4 for C_0	$C_2 = C_e \times T \times L$ See Table 3A-4b for C_e
Conveyor (Belt speed = 1.5 x standard)	3-3	$C_1 = [3 \times 8.88 + (0.0105/1.75)T]L/2$ $C_3 = (HP/mile)(dollars/HP\text{-}hr)L/2$	$C_2 = C_m \times L$ See Table 3A-5 for C_m
Hydraulic (30% solids)	3-6	$C_1 = (0.016 \times T + 5.71)L/2$	$C_2 = (80,000 + 79.22 \times T)L$
Monorail	4-7	$C_1 = C_0 \times T \times L/2$ See Table 3A-6a for C_0	$C_2 = C_e \times T \times L$ See Table 3A-6b for C_e

C_3 = energy cost, dollars/hour.
C_m = conveyor cost, dollars per mile.
C_e = specific equipment cost, dollars per ton/hour per mile.
C_0 = specific operating cost, dollars/hour per ton/hour per mile.

T = tons/hour
L = maximum system length, miles.

TABLE 3A-3

SPECIFIC COSTS FOR LOCOMOTIVE DRIVE SYSTEMS

a. SPECIFIC OPERATING COSTS, C_0
(Dollars/hour)/(ton/hour)(mile)

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	0.34	0.08	0.06	0.03
500	0.20	0.056	0.031	0.016
750	0.142	0.030	0.026	0.012
1,500	0.142	0.023	0.012	0.007

b. SPECIFIC EQUIPMENT COSTS, C_e
Dollars/(tons/hour)(mile)

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	1,225	425	360	240
500	840	330	250	163
750	650	300	185	150
1,500	650	205	140	90

TABLE 3A-4

SPECIFIC COSTS FOR TRUCK SYSTEMS

a. SPECIFIC OPERATING COSTS, C_0
(Dollars/hour)/(ton/hour)(mile)

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	0.05	0.05	0.05	0.026
500	0.05	0.032	0.032	0.023
750	0.05	0.032	0.026	0.022
1,500	0.05	0.030	0.025	0.022

b. SPECIFIC EQUIPMENT COSTS, C_e
Dollars/(tons/hour)(mile)

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	213	213	213	165
500	213	162	162	189
750	213	162	162	179
1,500	213	154	157	179

TABLE 3A-5

CONVEYOR EQUIPMENT COSTS, C_m
Dollars per Mile

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	287,000	287,000	287,000	327,000
500	287,000	287,000	404,000	404,000
750	287,000	287,000	404,000	830,000
1,500	287,000	404,000	655,000	983,000

TABLE 3A-6

SPECIFIC COSTS FOR MONORAIL SYSTEMS

a. SPECIFIC OPERATING COSTS, C_0
(Dollars/hour)/(tons/hour)(mile)

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	0.12	0.065	0.045	0.035
500	0.12	0.055	0.045	0.032
750	0.12	0.045	0.030	0.025
1,500	0.055	0.032	0.025	0.022

b. SPECIFIC EQUIPMENT COSTS, C_e
Dollars/(tons/hour)(mile)

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	1,300	1,100	950	900
500	1,200	900	800	700
750	1,100	650	575	575
1,500	680	420	360	360

VERTICAL OR INCLINED TRANSPORT

The transport modes analyzed for vertical or inclined lifting of materials include the siderail, hoist, and hydraulic systems for transport through vertical shafts and the side-wheel drive, cable drive, and conveyor systems for use in inclined shafts or tunnels. These systems are discussed in Chapters 3 and 4. In general, the cost estimating relationships summarized in Table 3A-7 are derived from data in Appendix 3B. Energy cost is included in the expressions for operating cost. Equipment costs for inclined conveyor systems are given in Table 3A-8 for a 26 percent inclined conveyor lifting material 1,000 feet vertically.

TABLE 3A-7

COST ESTIMATING RELATIONSHIPS FOR VERTICAL AND INCLINED TRANSPORT

Transport Mode	Reference Figure	Cost Estimating Relationship	
		Operating Cost (C_1) (Dollars/Hour)	Equipment Cost (C_2) (Dollars)
Side-Wheel Drive (26% incline)		$C_1 = (1.1173T^{-0.44})T \times D_1 \times 10^{-3}$	$C_2 = (62{,}180T^{-0.652}) \times T \times D_1 \times 10^{-3}$
Siderail (Vertical)	5-7	$C_1 = D_1 \times T(0.9558 - 0.0605 \text{ Log } T - 0.040 \text{ Log } D_1)$	$C_2 = D_1 \times 78 + D_1 \times T(4.774 - 0.349 \text{ Log } T - 0.169 \text{ Log } D_1)$
Cable Drive (Inclined)	5-2	$C_1 = D_1 \times T(-0.7197)T^{-0.657} \times (-0.658)D_1^{-0.626})$	$C_2 = D_1 \times T(324 + 186{,}312/T - 335 + 168{,}078/D_1)$
Hoist (Vertical)	5-1	$C_1 = D_1 \times T(0.853 \times 10^{-3} - 0.49 \times 10^{-4} \text{ Log } T - 0.5 \times 10^{-4} \text{ Log } D_1)$	$C_2 = D_1 \times T(5.36 - 0.244 \text{ Log } T - 0.364 \text{ Log } D_1)$
Conveyor (26% incline)	5-4	$C_1 = [D_1/(0.26 \times 5{,}280)] \times T(0.024/1.75) + (6 \times 9.75)$	See Table 3A-8
Hydraulic (Vertical)	3-6	$C_1 = D_1 \times T \times 10^{-3} \times (T^{-0.634} \times D_1^{-0.658} \times e^{6.603})$	$C_2 = D_1 \times T \times 10^{-3} \times (426 - 0.00368T + 0.0147D_1)$

T = Tons/Hour

D_1 = Vertical Height (feet)

TABLE 3A-8

INCLINED CONVEYOR EQUIPMENT COSTS
Dollars (Thousands)

1,000 Feet Vertical Height, 26% Incline

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	480	480	860	1,343
500	480	480	1,343	1,343
750	480	480	1,343	1,343
1,500	480	860	1,343	1,850

INTERMODE TRANSFER

In Chapter 5, concepts for transfer of material from horizontal to vertical transport in the shaft station were discussed and shown pictorially. These schemes included the use of an apron conveyor for transfer from a conventional rail system to a hoist, a hopper and reversible apron feeder arrangement for transfer from a conveyor to a hoist, and a surge bin with discharge chutes for loading from a conveyor into a vertical application of the siderail transport mode.

Table 3A-9 summarizes the cost estimating relationships used to obtain operating and equipment costs for these transfer schemes. Tables 3A-10 and 3A-11 give the equipment costs used for the hoist loading mechanisms for various advance rates and tunnel diameters. Operating costs are assumed to be equal to crew cost necessary to operate and maintain the installation because energy cost and cost of repair parts were found to be small compared to labor cost for comparable mechanical systems. Equipment costs for the hoist loading schemes are based on several similar installations for apron conveyors and bin type storage which were used as reference points. Engineering estimates were used to complete the range of installation sizes required to accommodate the capacity for various advance rates and tunnel diameters.

TABLE 3A-9

COST ESTIMATING RELATIONSHIPS FOR INTERMODE TRANSFER

Transfer		Reference Figure	Cost Estimating Relationship	
From	To		Operating Cost (C_1) (Dollars/Hour)	Equipment Cost (C_2) (Dollars)
Conventional Rail or Truck	Hoist	5-1	$C_1 = R_a(D \times A/1{,}000)$	See Table 3A-10
Conveyor	Hoist	5-3	$C_1 = R_a(D \times A/1{,}000)$	See Table 3A-11
Conveyor or Horizontal Siderail	Vertical Siderail	5-6	$C_1 = 9.75(4 + D \times A/4{,}000)$	$C_2 = 10 \times D \times A$

A = Tunnel advance rate in feet per 24-hour day.

D = Tunnel diameter in feet.

R_a = Average wage rate in dollars per hour per man for a crew composed of 60 percent laborers, 20 percent dumpers, and 20 percent mechanics. Wage rates from Chapter 12.

TABLE 3A-10

CONVENTIONAL RAIL OR TRUCK/HOIST TRANSFER EQUIPMENT COSTS
Dollars (Millions)

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	0.252	0.314	0.334	0.475
500	0.255	0.362	0.533	0.790
750	0.258	0.440	0.780	1.300
1,500	0.316	0.880	2.13	4.20

TABLE 3A-11

CONVEYOR/HOIST TRANSFER EQUIPMENT COSTS
Dollars (Thousands)

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	94	126	175	210
500	97	150	244	330
750	100	180	340	460
1,500	128	330	570	890

SYSTEM LOADING AND EXTENSION

Transport systems based on a guideway such as conventional rail, siderail, or monorail require, immediately behind the excavation equipment, a constantly moving work zone where guideway extension is performed simultaneously with switching, loading, and unloading of transport modules. One concept for providing this moving work zone is the Card Tunnelveyor* which makes use of a traveling platform or sliding floor carrying sections of track, track switches, short conveyors for muck loading, and other equipment for performing essential operations such as track laying which takes place ahead of the platform. This concept is discussed in Chapter 4.

It is reasonable to assume that, as the rate of tunnel advance increases, the length of trains in loading and unloading stations also will increase. The length (designated L_5) of the sliding floor assumed for various tunnel advance rates is given in Table 3A-12.

TABLE 3A-12

SLIDING FLOOR LENGTH, L_5

Advance Rate (Feet per Day)	Length (Feet)
300	400
500	500
750	625
1,500	1,000

Cost estimating relationships for equipment and operating costs associated with the various equipment units (referred to as subsystems) and functions required for loading and extension of the various modes of horizontal transport are summarized in Table 3A-13. The total cost for loading and extension of a particular transport mode is obtained by summing the operating cost (C_1), equipment Cost (C_2), and energy cost (C_3) for the equipment and work elements appropriate to the concept visualized. The energy costs associated with these equipment subsystems are trivial except for the short conveyors and a few cases where energy cost is included with the crew cost. For short conveyors the maximum energy cost for any configuration ($4.50 per hour) has been included for C_3.

*Tradename for conventional rail system loading and extension concept developed by C. S. Card Corporation of Denver, Colorado.

TABLE 3A-13 COST ESTIMATING RELATIONSHIPS FOR LOADING AND EXTENSION

Loading or Extension Unit	Cost Estimating Relationship			
	Operating Cost			Equipment Cost, C_2 (dollars)
	Labor		C_1 (dollars/hour)	
	Class (assumed)	Rate, R ($/hr)		
Sliding Floor	Muck Machine Operators	7.98	$C_1 = N \times R$ See Table 3A-14a for N	$C_2 = 1.1(80{,}000 + D \times 2{,}000) + 30{,}000(L_5/120 - 3)$ See Table 3A-12 for L_5
Short Conveyors	Muck Machine Operators	7.98	$C_1 = N \times R$ See Table 3A-14b for N	$C_2 = E \times L_5$ See Table 3A-15a for E
Loading, Locomotive Drive	Muck Machine Operators	7.98	$C_1 = N \times R$ See Table 3A-14c for N	$C_2 = E \times L_5$ See Table 3A-15b for E
Loading, Side-Wheel Drive	Muck Machine Operators	7.98	$C_1 = N \times R$ See Table 3A-14d for N	$C_2 = 50 \times L_5$
Loading and Extension, Siderail or Monorail	Master Mechanics	9.75	$C_1 = R(2 + D \times A/3{,}000) + R_T\ A/24$	$C_2 = 10 \times D \times A/24$
Extension, Conventional Rail	Track Boss and Crew	6.55	$C_1 = R(0.8 \times N_T \times A/24)$	Material cost included in horizontal transport subsystem.
Extension and Loading, Hydraulic	Pipe-fitters	9.67	$C_1 = R(D \times A/1{,}000)$	$C_2 = 300{,}000$/tunnel
Crushing, Hydraulic	Master Mechanics	N. A.	$C_1 = 0.224 \times T$	$C_2 = 44{,}000 (T < 500)$ $C_2 = 44{,}000 + T \times 56 (T > 500)$
Extension, Conveyor	Master Mechanics	N. A.	$C_1 = N \times R$	Material cost included in horizontal transport subsystem.

T = material rate, tons per hour.
D = tunnel diameter, feet.
N = number in crew.

N_T = number of dual rail tracks.
A = advance rate, feet/24-hour day.
R = labor rate, dollars/man-hour.

R_T (siderail) = $45/ft single track; $90/ft double track.
R_T (monorail) = $50/ft, D = 10; $75/ft, D = 20; $150/ft, D = 30; $350/ft, D = 40.
E = equipment cost, $/ft; L_5 = length of sliding floor, feet.

Sliding Floor

Operating Cost (C_1) - Operating costs are set equal to crew costs for this subsystem. In present-day practice the crew required to operate the sliding floor consists of two to three men - an operator and one or two laborers cleaning up ahead and maintaining the system. For higher advance rates and larger diameter tunnels, larger sized crews are expected to be required. The crew sizes projected and used in the analysis are given in Table 3A-14a.

Equipment Cost (C_2) - Equipment costs are based on estimates provided by Jacobs.* The costs for a unit consisting of 130 feet of lead track, 120 feet of passing track, and 120 feet of trailing track for a 12- to 18-foot diameter tunnel total about $100,000. For a 20- to 25-foot diameter tunnel, a cost of $120,000 is estimated for a unit of similar length. For longer units, more passing sections would be added. These sections are estimated to cost about $30,000 each. An additional 10 percent is added for transportation to the site. The estimating relationship derived from this data is given in Table 3A-13.

Short Conveyor Subsystem

Operating Cost (C_1) - The operating costs for short conveyors are equal to the crew costs required to operate and maintain the subsystem. A minimum crew of two men per 250 feet of short conveyor sections is included. For larger capacity systems, two parallel conveyor sections are included to maintain reliability and operational flexibility. The total crew for each diameter and advance rate is shown in Table 3A-14b.

Equipment Cost (C_2) - Short conveyor equipment costs are derived from the conveyor system model developed in Appendix 3B. The costs per foot of short conveyor section used in the analysis are shown in Table 3A-15a.

Energy Cost (C_3) - The maximum energy cost for any configuration has been included for C_3; this is $4.50 per hour.

*Jacobs Engineering Associates, San Francisco, California.

TABLE 3A-14

CREW SIZE
Number in Crew, N

a. Sliding Floor Operation

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	2	2	3	4
500	2	3	3	4
750	3	4	4	4
1,500	4	5	5	5

b. Short Conveyor Operation

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	2	2	3	3
500	2	3	3	4
750	2	3	4	5
1,500	3	4	5	7
	Single Conveyors	Double Conveyors		

c. Loading Locomotive Drive

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	3	3	5	6
500	3	4	6	7
750	4	6	7	8
1,500	5	7	8	9

TABLE 3A-14 (continued)

d. Loading Side-Wheel Drive System

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	2	2	3	3
500	2	3	3	4
750	3	4	4	4
1,500	4	5	5	5

e. Conveyor System Extension

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	4	4	4	4
500	4	4	4	5
750	4	4	5	6
1,500	4	7	9	11

TABLE 3A-15

EQUIPMENT COSTS, E

a. Short Conveyors

Dollars per Foot of Conveyor Length

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	103	103	206	206
500	103	206	206	228
750	103	206	228	324
1,500	206	228	324	432
	Single Conveyors	Double Conveyors		

b. Locomotive System Loading

Dollars per Foot of Length

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	110	110	285	434
500	110	385	385	434
750	110	385	385	434
1,500	385	385	434	434

Loading, Locomotive Drive System

Operating Cost (C_1) - Operating costs are set equal to crew costs for this subsystem. In present-day practice, the crew required to operate the loading system consists of three men - a conveyor operator, a switch operator, and a monorail hoist operator. For higher advance rates and larger diameter tunnels which require dual-track systems, larger sized crews are expected to be required. The crew sizes projected and used in the analysis are shown in Table 3A-14c.

Equipment Cost (C_2) - Equipment costs shown in Table 3A-15b are based on an estimate provided by the Card Corporation* for present-day systems. Systems constructed to meet the requirements of future high advance rate and larger sized tunnel requirements will be both longer and larger. They will be built to accommodate higher speed haulage, larger capacity cars, and probably a double track.

The Card Corporation supplied basic cost data on a recently constructed loading unit. The unit consists of nine 30-foot sections. The total unit is 270 feet long and costs approximately $30,000, exclusive of short conveyors. The cost per unit length is approximately $110 per foot. This unit will handle cars with capacities up to 12 cubic yards.

For units necessary to accommodate larger cars and a double track, costs were projected using estimates of the structural steel required and costs per pound of steel for material and fabrication.

The costs of equipment used in the subsystem cost function are made a function of the length of the loading station and are presented without the cost of conveyors. The short conveyor lengths are considered to be a separate subsystem.

Loading, Side-Wheel Drive System

The loading mechanism envisioned for the side-wheel drive system incorporates a sliding floor for a foundation and short conveyors to transport material from the boring machine to the loading zone. The sliding floor would be equipped with a number of tracks (consistent with the tunnel width and loading requirements) on which the side-wheel drive trains can be shuttled in sequence. Power units are assumed to be located at appropriate intervals on each of the sidings to allow precise speed and position control of units entering, leaving, unloading, or loading in the zone.

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*C. S. Card Corporation, Denver, Colorado.

Operating Cost (C_1) - The operating costs represent the crew required to maintain and control the loading operations. Sliding floor and conveyor crews are accounted for by including these subsystems separately. The crew estimated to be required for the loading operation is shown in Table 3A-14d.

Equipment Cost (C_2) - Equipment costs for the power units and control required for the subsystem are a function of the loading system length. In the analysis, $50 per foot of loading system length has been used.

Loading and Extension, Siderail System

The siderail loading subsystem is assumed to be mounted on a sliding floor and fed by short conveyor sections. The loading system has not been designed in any detail, but the loading cycle requirements are expected to be of the order of seconds for each module. A very complex system, both in terms of operational requirements and equipment, is envisioned.

Operating Cost (C_1) - There is no experience upon which the crew size can be based; nevertheless, a crew size has been estimated for operation of the loader. The loading crew size used in the estimate ranges from 3 men for 100-ton per hour material flow rates to 22 men for 7,000 ton-per-hour flow rates. The expression used for crew size is

$$\text{Crew Size} = D \times A/3{,}000 + 2$$

In addition to the loading crew, guideway extension costs are included in this subsystem. Tracklaying costs are estimated to be $45 per foot for single track and $90 per foot for double track. This cost is derived in Appendix 3B, where the siderail system is discussed. The operating cost for track extension is

$$\$/\text{hr} = \$90 \times A/24$$

where A = ft/24-hr day.

Equipment Costs (C_2) - The function included for equipment cost is

$$\$ = 10 \times D \times A/24$$

Loading and Extension, Monorail System

The monorail loading and extension subsystem costs are obtained from the siderail cost functions described above. The costs are the same with the exception that tracklaying unit costs are assumed to be: 50 dollars per foot for 10-foot-diameter tunnels; 75 dollars per foot for 20-foot-diameter tunnels; 150 dollars per foot for 30-foot-diameter tunnels; and 350 dollars per foot for 40-foot-diameter tunnels.

Extension, Conventional Rail Systems

Operating Cost (C_1) - The operating costs for laying track are equal to the crew costs to perform this function. A standard labor estimating factor of 0.8 manhours per foot of track laid is used to size this crew. This factor is used where minimum bed preparation is required. For a double track at high advance rates, the crew size becomes greater than the tunnel space can accommodate; so it is assumed that part of the labor is used to prepare prefabricated sections outside the tunnel or that an equivalent expense for automated equipment would be incurred. The 0.8 manhour-per-foot estimate used in the analysis accounts for these alternate costs.

Equipment Cost (C_2) - Material costs are included in the horizontal transport subsystem.

Extension and Loading, Hydraulic System

Operating Cost (C_1) - This subsystem would require rather complicated devices in the near-face zone to extend the pipe while maintaining continuous flow. Another complication is crushing the muck to obtain the desired level of fines. The crew size and operating costs for the pipe extension equipment; installation and operation of pumps, control devices; and installation of pipe support brackets are estimated without the benefit of a detailed analysis of these operations by the relationship given in Table 3A-13.

Equipment Cost (C_2) - The analysis assumes that the pipe extension, pumping, and control equipment would be mounted on a sliding floor and be fed by short conveyors. The cost for the extension, pumping, and control equipment is estimated to be $300,000 per tunnel system. The estimate is based on judgment reflecting the complexity of the equipment.

Crushing for Hydraulic System

Operating Cost (C_1) - Crushing costs including crew and energy costs are based on data from several literature sources. The cost used in 1970 dollars is $0.224 per ton of material crushed.

Equipment Cost (C_2) - Eimco* manufactures a horizontal crusher with potential for tunnel operation. Costs provided are:

1,000 tph (60 x 66 inch), $100,000

500 tph (36 x 42 inch), $ 44,000

It is assumed that for low tonnage rates, the minimum cost for crushing equipment would be $44,000. The parametric expression which fits these estimates and is used in the analysis is:

$$\$ = 44{,}000 + T \times 56$$

where $T > 500$ tph

$$\$ = 44{,}000$$

where $T < 500$ tph

Extension, Conveyor System

Operating Cost (C_1) - The operating costs for conveyor system extension are equal to the cost of the labor crew. Estimated crew size is given in Table 3A-14e.

Equipment Cost (C_2) - The equipment cost for conveyor system extension is insignificant. Material costs are included in the horizontal transport subsystem cost.

SETUP COST (C_4)

Setup costs, in general, cover the assembly and check-out of material handling equipment after it has been moved into each new tunnel segment working zone. In most cases this has been established as a factor of the appropriate operating cost, C_1, which includes costs for the normal operating and maintenance crews for the system. Deviations from the general rule were made when a more reliable estimate could be obtained by introducing other factors. The cost functions and time factors are described in Table 3A-16 and the deviations are described in the following notes. Setup costs are obtained by multiplying the cost function by the time factor.

*Eimco Division of Envirotech Corporation, Salt Lake City, Utah.

TABLE 3A-16

ESTIMATING RELATIONSHIPS FOR SETUP COST (C_4)
(Dollars)

Item	See Note	Time Factor (hours)	Cost Function ($/hr)
HORIZONTAL TRANSPORT			
Locomotive Drive	4	120	x (D x A/1000) 8.88
Side-Wheel Drive		120	x C_1
Siderail and Monorail		120	x C_1
Truck	7	0	
Conveyors	5	120	x 8.80 x N See Table 3A-14b for N
Hydraulic	6	100	x 9 x 9.75
VERTICAL OR INCLINED TRANSPORT			
Side-Wheel Drive (inclined)		180	x C_1
Siderail (vertical)	13	480	x 10 x 8.88
Cable Drive (inclined)	11		C_2 x F + D_1/S_7 x 0.8 x 2 x 6.55 See Table 3A-17 for F
Hoist (vertical)	10		C_2 x F See Table 3A-17 for F
Conveyor (26% incline)	12	0	
Hydraulic (vertical)	9	120	x 6 x 9.75 + D_1 x 10
INTERMODE TRANSFER			
Rail or Truck to Hoist	8	0	
Conveyor to Hoist		240	x C_1
Conveyor to Siderail		120	x C_1
LOADING AND EXTENSION			
Sliding Floor		120	x C_1
Short Conveyors	2		8.08 x L_5 x N See Table 3A-14b for N
Locomotive Drive	1	0	
Side-Wheel Drive		120	x C_1
Siderail and Monorail		120	x C_1
Conventional Rail Extension		480	x C_1
Hydraulic	3	120	x (D x A/1000)(9.67)

Note

L_5 = Sliding floor length, feet.

D_1 = Vertical height, feet.

S_1 = Slope, percent.

Notes to Table 3A-16

1. The conventional rail loading system comes in sections which require little or no setup labor.

2. The labor required by the short conveyor for setup is proportional to the length of short conveyors used. Based on the expression shown, from 2 to 3.5 manhours per foot of conveyor are required for setup. (See Table 3A-14b.)

3. The crew for hydraulic extension is used for setup of this subsystem. The crew is a function of tunnel diameter and advance rate.

4. Setup of the locomotive drive system covers location, reassembly, and check-out on the rolling stock required. The crew required to accomplish this is estimated to be proportional to tunnel diameter and advance rate.

5. The crew established for extending the conveyor system is also used during setup. The time period is 120 hours and the average labor rate is $8.88 per hour.

6. Setup of the hydraulic system consists of initial setup of pump and electrical power supplies. This is estimated to require a crew of nine for 100 manhours at a labor rate of $9.75 per hour.

7. The setup time for vehicles is included in mobilization costs.

8. The setup costs for this subsystem are included in the mobilization costs.

9. The setup costs for vertical hydraulic systems require an operating crew of six for 120 hours plus $10 per foot of shaft depth for pipe installation.

10. A special matrix of cost factors has been estimated for this function. The cost factors applied to the equipment are given in Table 3A-17. To find the setup cost, multiply each factor times the appropriate value of C_2.

11. The cable drive system uses the same function as used for hoists because similar equipment is used for hoisting. In addition, a cost for laying two sets of railway tracks is included.

12. Setup costs for inclined conveyors are included in mobilization costs.

13. Setup costs for siderail equipment are based on ten men, 480 hours, at a labor rate of $8.88 per hour.

TABLE 3A-17

SPECIAL FUNCTIONS (F) FOR SETUP COSTS

Advance Rate (Feet per Day)	Tunnel Diameter (Feet)			
	10	20	30	40
300	0.25	0.20	0.18	0.12
500	0.25	0.18	0.12	0.10
750	0.20	0.18	0.12	0.10
1,500	0.20	0.12	0.10	0.10

MOBILIZATION COST (C_5)

The system concepts evaluated are required to be highly mobile or flexible in all cases. Each tunnel segment under construction requires that the material handling system be moved to the location and installed or reassembled. Following the use of each equipment set, the equipment must be disassembled, hauled out of the tunnel to a new site, and reassembled (usually underground). Setup costs, summarized in the previous section, are incurred to return the system to operating condition. It must be assumed that the equipment used in this manner is designed with mobility in mind. Compared with a material handling system used in a permanent mine installation, equipment for a tunnel application should be designed for disassembly in sections which are bolted together rather than riveted or welded. The use of temporary foundations, such as skids, and less permanent electrical connections is a necessity. These types of design innovations could lead to higher costs compared with permanent installations. The study assumes that permanent and semi-mobile designs required for rapid tunneling cost an equal amount. The mobilization costs and the time period involved to conduct a mobilization cycle are assumed to be much less than for permanent installations.

Mobilization cost factors are, in general, based upon the operating costs of the particular system which include the crew costs; repair costs; and, in some cases, energy costs. The mobilization costs are generated by multiplying the hourly operating costs by some fixed time period. There are numerous deviations from the general case. The cost factors are summarized in Table 3A-18 along with the special cases described in the following notes.

TABLE 3A-18

ESTIMATING RELATIONSHIPS FOR MOBILIZATION COST (C_5)

(Dollars)

Item	See Note	Time Factor (hours)	Cost Function ($/hr)
HORIZONTAL TRANSPORT			
Locomotive Drive	5	240	x (D x A/1000)8.88 + 15 x L x 5280
Side-Wheel Drive		360	x C_1
Siderail	9	240	x C_1 + 10 x 9.0 x 240
Truck	8	120	x 20 x 9.00
Conveyors	6	240	x 8.88 x N See Table 3A-14e for N
Hydraulic	7	120	L x 6 x 9.67
Monorail		240	x C_1 + 10 x 9.0 x 240 + 77 x L x 5280
VERTICAL AND INCLINED TRANSPORT			
Side-Wheel Drive (26% incline)			26 x (D_1/S_7)
Siderail (vertical)	14	480	10 x 8.88
Cable Drive (inclined)	12	240	x C_1 + 0.5 x C_4
Hoist (vertical)	12	240	x C_1 + 0.5 x C_4
Conveyor (26% incline)	13		26 x (D_1/S_7)
Hydraulic (vertical)	11		2 x C_4
INTERMODE TRANSFER			
Rail or Truck to Hoist	10		C_2 x 0.5
Conveyor to Hoist		240	x C_1
Conveyor to Siderail		240	x C_1
Horizontal Siderail to Vertical Siderail		240	x C_1
LOADING AND EXTENSION			
Sliding Floor		240	x C_1
Short Conveyors	2		8.08 x L_5 x N See Table 3A-14b for N
Locomotive Drive	1	60	x 6.55 x N See Table 3A-14c for N
Side-Wheel Drive		240	x C_1
Siderail and Monorail	3	240	x C_1 + 45 x L x 5280
Conventional Rail Extension		240	x C_1
Hydraulic	4	120	x C_1 + (D x A/1000)9.67

Notes to Table 3A-18

1. The car loading system assumed for locomotive drive systems consists of easily transportable sections which can be rolled down the existing track to the portal. It is estimated that a crew equal in size to the tracklaying crew could completely move the loading system in 60 hours. The tracklaying labor classification is also assumed.

2. A crew is defined for operating and maintaining the conveyor sections. This function assumes that the same crew is used to remove and transport the sections to a new site. The actual time required by the crew is made proportional to the length of the conveyor system (L_5), which results in manhours of from 2 to 3.5 per foot of conveyor.

3. The cost of one set of tracks, left behind for finishing the tunnel, is added to this term. Siderail track material costs are approximately $45 per foot. Monorail costs for track materials are a function of tunnel diameter, discussed under equipment costs in a previous paragraph.

4. A crew is defined for operating and advancing the hydraulic transport equipment near the tunnel face and also to mobilize this equipment. Crew size is based on diameter and advance rate. Hence, the function D x A/1,000 for crew size, 120 hours for the time period, and $9.67 per hour for the labor rate.

5. The cost of one set of track left behind for finishing the tunnel is added to allow the completion of the tunnel ($15 per foot x L in miles x 5,280). In addition, the tracklaying crew is maintained for an additional 240 hours.

6. A crew size is established for extending conveyors. It is assumed in this function that this crew is required for 240 hours during the mobilization phase.

7. Removal of hydraulic pipeline and pumps is estimated to require six men, 120 hours per mile of tunnel (720 manhours per mile at $9.67 per hour).

8. Vehicles are disassembled and moved to the surface, hauled or driven to a new location, and relocated underground. The average system has 20 vehicles, and if disassembly is involved, 120 hours of $9.00 per hour labor is included.

9. Siderail mobilization costs consist of two elements. Movement of modules to a new location is estimated to require 240 hours of operating time. Movement of supporting electrical equipment and controls would require an additional 10 men for 240 manhours.

10. This subsystem consists of apron conveyors located in a troughed pit. The cost of building the pit cannot be recovered. Construction estimating techniques yield mobilization and installation cost proportional to equipment costs of 50 percent.

11. Mobilization costs for vertical hydraulic systems are estimated to be two times the setup costs or $20 per foot of shaft depth for installing the piping. The hydraulic system crew (six men) is included for 120 hours for disassembly and movement of the pumping unit.

12. Mobilization of the hoist for the skiphoist and cable assist systems is estimated as a factor of setup costs and operating costs. The mobilization cost is estimated to be one-half the setup costs, C_4. In addition, the normal operating crew is required for 240 hours.

13. Conveyor mobilization costs are estimated to be $26 per foot.[2]

14. A crew of ten men working 480 hours with a labor rate of $8.88 per hour is estimated for mobilizing this system.

DEVELOPMENT AND ENGINEERING COST (C_6)

The equipment required to support the high advance rates being considered in this study ranges from state-of-the-art equipment used in a highly scheduled and sequenced mode of operation to new and novel designs which would require specialized research and development programs. It is anticipated that equipment required for functions such as extending the slurry system while maintaining flow or loading modules at high speed in tunnels would be highly specialized with little demand outside tunnel construction, or even a particular tunneling project. This requires that development of equipment in this class be charged to the project or to a series of projects.

This introduces one of the imponderables of distributing development or engineering costs among systems. The number of systems cannot be predicted; hence, even if these costs are known, the cost per unit is difficult to predict. This restriction, as well as the uncertainty of determining the basic development costs for specialized equipment before preliminary design studies have been conducted, results in cost estimates of low confidence for this equipment. Costs for this cost element are included as summarized in Table 3A-19.

Equipment which falls more closely into variations of state-of-the-art equipment will require some engineering costs which in this study are estimated as a percentage of acquisition costs, guided by engineering rule of thumb. Table 3A-19 also shows the percentages applied. Where no cost is included, it may be assumed that the cost is trivial or included in the equipment acquisition cost.

TABLE 3A-19

ESTIMATING RELATIONSHIPS FOR ENGINEERING AND DEVELOPMENT COST (C_6)
(Dollars)

Item	Equipment Cost Factor (per system)	Cost Function (dollars)
HORIZONTAL TRANSPORT		
Locomotive Drive	0.02	C_2
Side-Wheel Drive	0.10	C_2
Siderail and Monorail	0.25	C_2
Truck		200,000
Conveyors	0.05	C_2
Hydraulic	0.05	C_2
VERTICAL TRANSPORT		
Side-Wheel Drive (inclined)	0.40	C_2
Siderail (vertical)		110,000
Cable Drive (inclined)	0.10	C_2
Hoist (vertical)	0.05	C_2
Conveyor (26% incline)	0.05	C_2
Hydraulic (vertical)		100,000
INTERMODE TRANSFER		
Rail or Truck to Hoist	0.02	C_2
Conveyor to Hoist	0.04	C_2
Conveyor to Siderail		100,000
LOADING AND EXTENSION		
Sliding Floor		50,000
Short Conveyors	0	
Locomotive Drive	0	
Side-Wheel Drive	0.1	C_2
Siderail and Monorail		10 x D x A
Conventional Rail Extension	0	
Hydraulic with Crushing		500,000

TRAINING AND SHAKEDOWN COST (C_7)

The system concepts evaluated for the material handling functions are based upon highly complex equipment requiring a high degree of worker skill, coordination, and teamwork. Developing crews which can perform tasks efficiently must be assumed to be a significant task. A comprehensive study of the tasks and time involved in training personnel and "shaking down" the systems is beyond this study; however, some general estimates of time were made in recognition of the significant time required for these functions. Normally 1 week (three 40-hour shifts) is allowed for this purpose. A factor which was considered in making this estimate is that the horizontal transport material handling system crew is generally based on the maximum operating length of the system. At the time when the tunnel segment is very short, the minimum equipment and crew are required to operate the system. This coincides with the time when equipment is being set up and operators are being trained. The best trained personnel can be utilized to operate the system, with training or setup continued simultaneously with other operations.

Another factor to be considered in interpreting the time allocated for training or shakedown is that it is a value averaged over several relocations and reuses of equipment. The crew will no doubt require more time for training and shakedown of equipment on the first tunnel segment than on those which follow. Hence, for a crew which works through several tunnel segments, 2 weeks might be required for initial training and shakedown; while on subsequent segments a few days might be adequate. Complexity of equipment sometimes makes the training and equipment shakedown tasks more complicated and time consuming than is generally the case.

The normal crew to operate the various systems are assumed to be necessary for training and shakedown functions, with several exceptions as indicated. Table 3A-20 shows the cost estimating relationships including the number of hours estimated to be required for training and shakedown and cost function to which the hours are applied. Normally this is the operating cost function (C_1, dollars per hour). These cost functions are based on construction estimates and engineering judgment.

TABLE 3A-20

ESTIMATING RELATIONSHIPS FOR TRAINING AND SHAKEDOWN COST (C_7)

(Dollars)

Item	Time Factor (hours)	Cost Function ($/hr)
HORIZONTAL TRANSPORT		
Locomotive Drive	120	x C_1
Side-Wheel Drive	120	x C_1
Siderail and Monorail	360	x C_1
Truck	120	x C_1
Conveyors	120	x C_4
Hydraulic	120	x (D x A/1000) x 9.67
VERTICAL TRANSPORT		
Side-Wheel Drive (inclined)	180	x C_1
Siderail (vertical)	180	x x 6 x 6.88
Cable Drive (inclined)	240	x C_1
Hoist (vertical)	120	x C_1
Conveyor (26% incline)	120	x C_1
Hydraulic (vertical)		C_4
INTERMODE TRANSFER		
Rail or Truck to Hoist	120	x C_1
Conveyor to Hoist	240	x C_1
Conveyor to Siderail	240	x C_1
LOADING AND EXTENSION		
Sliding Floor	120	x C_1
Short Conveyors		0.5 x C_4
Locomotive Drive	120	x[C_1 (loading) + C_1 (extension)]
Side-Wheel Drive	120	x[C_1 (loading) + C_1 (extension)]
Siderail and Monorail	240	x C_1
Conventional Rail Extension	-	- -
Hydraulic with Crushing	120	x (D x A/1000) x 9.67

Note

C_1 = Normal hourly operating cost.

C_4 = Appropriate function from Table 3A-16.

A = Advance rate, feet per 24-hour day.

D = Tunnel diameter in feet.

SALVAGE OR DISPOSAL VALUE (C_8)

Historically, permanent installations of material handling systems are amortized over their useful life, which is usually quite long compared to the life of a tunneling project. Some examples of equipment life are:

Equipment	Life (years)
Locomotives	17 to 40
Conveyor Equipment (Belts excepted)	10
Trucks	2 to 5

In a normal tunnel construction project, material handling equipment probably would not be worn out although it would be given unusually heavy usage. Contractors, in the past, have used varying policies for "writing off" those equipment costs - but for large quantities of specialized equipment the most prevalent policy is to conservatively "write it off" on the job for which it was purchased. For a large-scale tunneling project, this is likely to be the case.

This study assumes that most equipment has some depressed value for resale or salvage. The value depends upon factors such as

- Degree of specialty
- Life of various components
- Demand for use in other bulk material handling applications
- Cost of removal from tunnel.

In some cases, a value of zero is allocated since the cost of removal from the tunnel would about equal scrap value. In other cases, the value estimated is governed by the demand for salvageable key components such as heavy-duty electric motors.

Placing a salvage or disposal value on equipment allows the equipment cost (new cost minus salvage value) to be allocated to a tunnel project or to a series of projects (defined by the value given to M) and thereby amortize it in a reasonable fashion. The disposal or salvage values have, in all cases, been made a fraction of new equipment costs. The factors are constant regardless of the number of construction-use cycles being considered. Table 3A-21 presents the equipment cost factors applied in this study to obtain salvage values.

TABLE 3A-21

SALVAGE OR DISPOSAL VALUES (C_8)

(Dollars)

Item	Equipment Cost Factor (per system)	Cost Function (dollars)
HORIZONTAL TRANSPORT		
Locomotive Drive	0.3	$x\,C_2$
Side Wheel Drive	0.2	$x\,C_2$
Siderail and Monorail	0.3	$x\,C_2$
Truck	0.5	$x\,C_2$
Conveyors	0.07	$x\,C_2$
Hydraulic	0.3	$x\,C_2$
VERTICAL TRANSPORT		
Side Wheel Drive (inclined)	0.1	$x\,C_2$
Siderail (vertical)	0.3	$x\,C_2$
Cable Drive (inclined)	0.4	$x\,C_2$
Hoist (vertical)	0.4	$x\,C_2$
Conveyor (26% incline)	0.1	$x\,C_2$
Hydraulic (vertical)	0.3	$x\,C_2$
INTERMODE TRANSFER		
Rail or Truck to Hoist	0	
Conveyor to Hoist	0.1	$x\,C_2$
Conveyor to Siderail	0	
LOADING AND EXTENSION		
Sliding Floor	0	
Short Conveyors	0.1	$x\,C_2$
Locomotive Drive	0	
Side-Wheel	0	
Conventional Rail Extension	0	
Hydraulic	0.1	$x\,C_2$

MAINTENANCE SPARES (C_9)

The quantity and type of spare components and equipment required for each transport mode vary with the type of equipment being used and the maintenance policy, as illustrated by the following examples.

Transport Mode	Spare Equipment
Trucks	Truck Units, Tires
Locomotive Trains	Locomotives, Cars
Side-Wheel Drive Trains	Power Units, Special Portable Power Units, Cars
Siderail and Monorail Systems	Modules
Hydraulic Pipelines	Pump Units
Conveyors	Power Units, Idlers, Rollers, Belt

Expressing the cost of spare units in terms of a fraction of new equipment cost is common practice. Table 3A-22 presents the equipment cost factors applied in this study to obtain the cost of maintenance spares.

TABLE 3A-22

SPARES REQUIRED TO MAINTAIN THE SYSTEM (C_9)
(Dollars)

Item	Equipment Cost Factor (per system)	Cost Function (dollars)
HORIZONTAL TRANSPORT		
Locomotive Drive (Note 1)	0.10	$\times C_2$
Side-Wheel Drive	0.10	$\times C_2$
Siderail	0.10	$\times C_1$
Truck (Note 2)	0.40	$\times C_2$
Conveyors	0.10	$\times C_2$
Hydraulic (Note 2)	0.30	$\times C_1$
VERTICAL TRANSPORT		
Side-Wheel Drive (inclined)	0.10	$\times C_2$
Siderail (vertical)	0.10	$\times C_2$
Cable Drive (inclined)	0.10	$\times C_2$
Hoist (vertical)	0.10	$\times C_2$
Conveyor (26% incline)	0.10	$\times C_2$
Hydraulic (vertical)		
INTERMODE TRANSFER		
Rail or Truck to Hoist	0.1	$\times C_2$
Conveyor to Hoist	0	$\times C_2$
Conveyor to Siderail	0.2	$\times C_2$
LOADING AND EXTENSION		
Sliding Floor	0	
Short Conveyors	0.05	$\times C_2$
Locomotive Drive	0	
Side-Wheel Drive	0.05	$\times C_2$
Conventional Rail Extension	0	
Hydraulic	0.15	$\times C_2$

Notes

1. Extra train per system included in equipment costs. (Reference Appendix 3B.)
2. Included are complete spare pump units.

AVAILABILITY FACTORS

Availability terms have been included for each transport mode based on data or estimates of the particular system's ability to operate continuously at nearly full capacity. The series availability is used to represent the availability of the system and to make a distinction between the availability of the system and the availability of individual components. Two examples are presented to illustrate this distinction.

Conveyor segments represent components used in series. The chain of segments all must perform simultaneously in order for the system to be available. Should a key component fail, the whole system must be shut down until repairs are made. This adds significantly to the level of standby maintenance required to operate the system at high levels of availability. The fact that all segments are in series is, in fact, a disadvantage of the system. A redundant conveyor system would eliminate this disadvantage, but this would be a costly and impractical alternative.

For a modular or unitized system, the system availability is different than the product of component availabilities. For example, if a train system with a failed locomotive or car appeared, the failed unit would be towed to a siding and removed for repair. Spare units would be brought on line to continue the operation at full capacity. The system downtime would be minimized by this policy and in addition, this type of system can be operated at reduced capacity for short periods. Judgment was used to determine the extent to which each system is available at peak operating conditions or at acceptable but reduced utilization. The level of maintenance required to sustain a particular availability level has been considered in operating costs.

For horizontal transport systems, the length of the system has an effect on its availability. As the length of the system increases, it is likely that the availability will decrease. The availability is computed as a function of length. Since the length is variable with time, the average length is used in predicting the average availability. Availability predictions for other systems are constant value terms.

Table 3A-23 presents the availability factors used in the system model discussed in Chapter 14.

TABLE 3A-23

AVAILABILITY FACTORS

Item	Availability Factor
HORIZONTAL TRANSPORT	
Locomotive Drive	1 - 0.01 L/2
Side-Wheel Drive	1 - 0.04 L/2
Siderail and Monorail	1 - 0.01 L/2
Truck	0.933/0.95
Conveyors	1 - 0.02 L/2
Hydraulic	1 - 0.010 L/2
Pneumatic	1 - 0.02 L/2
VERTICAL TRANSPORT	
Side-Wheel Drive (inclined)	0.94
Siderail (vertical)	0.95
Cable Drive (inclined)	0.98
Hoist (vertical)	0.98
Conveyor (26%incline)	$1 - 0.02 (D_1/2 \times 5280)$
Hydraulic (vertical)	0.98
INTERMODE TRANSFER	
Rail or Truck to Hoist	0.98
Conveyor to Hoist	0.99
Conveyor to Siderail	0.95
LOADING AND EXTENSION	
Sliding Floor	0.99
Short Conveyors	1.0
Locomotive Drive	0.95
Side-Wheel Drive	0.99
Conventional Rail Extension	1.0
Hydraulic	0.92

Note

L = Length of tunnel segment, miles

D_1 = Vertical depth of tunnel, feet.

APPENDIX 3B

ANALYSIS OF TRANSPORT MODES

INTRODUCTION

The approaches developed and used in Chapters 12 through 15 are based on the independent analysis in substantial detail of each horizontal and each vertical transport mode. The outputs of these analyses are sets of parametric data, uniform in format, for the vertical and horizontal transport modes. These resulting data, in the form of cost/performance ratios for each system, are identified as specific operating and specific equipment costs since they are the cost of system operation or the initial cost (capital cost) of equipment expressed per unit of system capacity and per unit distance of transport. These results presented in chart form in this appendix are of interest for comparison of modes; however, the major use of the results of these analyses is as inputs to the integrated system analyses which compute overall costs of material handling in tunnels for various geometry and levels of performance.

The analysis approach used develops mathematical models of the various material transport system. These models are a set of equations for each transport mode, which computes the performance of the system and other physical parameters (such as size and horsepower) which are used to compute the cost of the system. Another set of equations computes the costs (equipment and operating) of the system based on the physical descriptors and other factors. In most cases a digital computer has been used to perform the computations and to develop estimating relationships from empirical data.

The performance of the material transport system has been computed and expressed as tons of material transported per hour. The equipment costs are computed in dollars and operating costs are computed in dollars per hour of operation. To express equipment cost in the same units as operating cost, it is necessary to determine or arbitrarily select a useful life in terms of hours of operation for the equipment, and divide the cost of the equipment by the useful life. The cost per unit capacity or performance is obtained by dividing the capacity into the equipment cost (dollars) and into the hourly operating cost (dollars per hour). Each ratio is also divided by the length (in miles for horizontal transport) or the vertical depth (in 1,000's of vertical feet for vertical or inclined lift systems).

As a result, two ratios are generated which are indicative of the cost/performance ratio of each system evaluated. The ratios are defined as follows:

Horizontal Transport

$$\text{Specific Equipment Cost} = \frac{\$}{(\text{tons/hr}) \times \text{miles}}$$

$$\text{Specific Operating Cost} = \frac{\$/\text{hr}}{(\text{tons/hr}) \times \text{miles}} = \frac{\$}{\text{ton-mile}}$$

Vertical or Inclined Transport

$$\text{Specific Equipment Cost} = \frac{\$}{(\text{tons/hr}) \times (\text{ft}/1000)}$$

$$\text{Specific Operating Cost} = \frac{\$/\text{hr}}{(\text{tons/hr}) \times (\text{ft}/1000)}$$

These ratios are a function of the hourly capacity of the system. The results of the system analysis are plots of the above cost/performance ratios against system capacity (tons per hour). In order to convert the specific equipment and operating cost terms back to system equipment costs (dollars) or system operating costs (dollars per hour), the function value used must be the appropriate value for the system capacity being considered. After determining either function (specific operating cost or equipment cost), the value must be multiplied by the hourly capacity in tons per hour and by the length in miles or depth in 1,000 feet, as appropriate. Tons/hr is selected as a general but adequate performance measure for the material handling systems because it can be made a function of variations in advance rate, tunnel diameter, and material density, as well as the many other factors which describe a given tunneling situation.

This appendix describes analytical models and cost/performance results for the systems in Table 3B-1 which were selected for the attitudes of transport indicated. For each system, equations are presented for the performance followed by equations for the cost. A third section presents the system cost/performance results which are ratios, presented in chart form, of the previously developed cost and performance.

In almost all cases basic cost data are presented in 1970 U. S. dollars. Where this is not the case, the cost data conditions are noted.

TABLE 3B-1

TRANSPORT MODES ANALYZED

System	Horizontal	Vertical (or inclined)
Conveyor	X	X
Side Wheel Drive	X	X
Pneumatic	X	X
Trucks	X	
Siderail	X	X
Locomotive Drive	X	
Hydraulic	X	X
Hoist		X
Cable Drive		X
Monorail	X	

CONVEYOR SYSTEM

Performance

The conveyor performance is modeled by using standard conveyor design equations and tables in parametric form. It was found that the expression

$$V = 330 + 4.5W$$

where

$$W = \text{belt width in inches}$$

and

$$V = \text{velocity in feet per minute}$$

closely approximates conveyor belt speeds recommended for muck. The material flow cross-sectional area established in various sources of design information was also found to be a function of W. The relationship is

$$A = 0.0007W^2$$

where

$$A = \text{feet}^2 \quad .$$

The computerized performance model uses these basic relationships to compute the volumetric capacity (cubic yards per hour) and the mass flow capacity (tons per hour) for a particular material density, using the relationships

$$yd^3/hr = AV \frac{60}{27}$$

and

$$ton/hr = \frac{AV\ 60\rho_s}{2,000}$$

where

ρ_s = bulk density (pounds per cubic foot after the swell factor is applied.

The horsepower for the conveyor is computed as a function of length, using standard conveyor equations established in many design references. The total horsepower equation is

$$HP_{TOTAL} = HP_B + HP_L + HP_H + HP_I$$

where

HP_B = belt friction horsepower,

HP_L = load friction horsepower,

HP_H = vertical lift horsepower,

and

HP_I = inertial load horsepower.

$$HP_B = \frac{C(L + 100)(0.03\ qV)}{990}$$

where

L = length of conveyor section (feet),

C = friction coefficient (0.03),

and

q = rolling mass (established as a function of width);

$$HP_L = \frac{C(L + 100)\ ton/hr}{990} \quad ;$$

$$HP_H = \frac{(ton/hr) \times H}{990}$$

where

H = vertical lift height in feet;

and

$$HP_I = \frac{(ton/hr)\ V^2}{15 \times 10^6} \quad .$$

Belt tension, idler roller spacing, and return roller spacing were also computed using approximating equations.

Cost

The conveyor system costs were computed by generating cost estimating functions for the belt, rollers, structure, end equipment (including motors), and the fabrication labor. Costs on a more aggregate basis also were collected and checked against the model developed on a component level (see Figure 3B-1). The correlation between aggregate cost data and the system model was sufficiently close; but the aggregate cost data did not cover all parametric ranges, so the component level model was retained to generate data shown in the next section.

Component Costs

Cost data for belt, rollers, and end equipment are from Holmes & Narver, Inc. projects involving quantity buys. These components were found to have cost estimating relationships (CER) of:

Belt Cost, C_B ($\$/W \times L_B$) = $0.027 + 0.015W$ (see Figure 3B-2)

End Equipment, \$/HP = $246\ HP^{(-0.1936)}$

Idler Rollers, \$ = (No. Rollers)(2.12 + [W - 8) 0.885)] + W x 200

Return Rollers, \$ = (No. Rollers)[10.6 + (W x 0.505)]

Labor to construct portable sections or prefabricated sections was estimated to be \$ = 240 + 15L. The structural steel requirements were estimated to be equal to 1 pound per inch of width per foot. Cost was estimated to be \$0.20 per pound.

Costs of maintenance were based on 2 men per mile plus \$0.022 per cubic yard of material moved per mile. Power costs were based on \$0.015 per kilowatt hour and efficiencies of 74 percent.

The belt CER is developed on Figure 3B-2. The CER for motors, gearboxes, and other horsepower-related end equipment is developed on Figure 3B-3 from Holmes & Narver data in the lower horsepower range and data from Reference 1 at 1,000 horsepower. This cost function is particularly important for conveyors operating at maximum slopes since these units require high horsepowers compared with horizontal transport units. The maintenance costs (\$0.022 per cubic yard per mile) were based on Reference 1 and reflect the maintenance level required to maintain a large earth-filled dam conveyor (Oroville Dam, California) which was approximately 5 miles in length with an availability of 90 percent. In addition, 2 men per mile were added for tunneling conditions. The labor estimate for prefabricating conveyor segments is based on Reference 2.

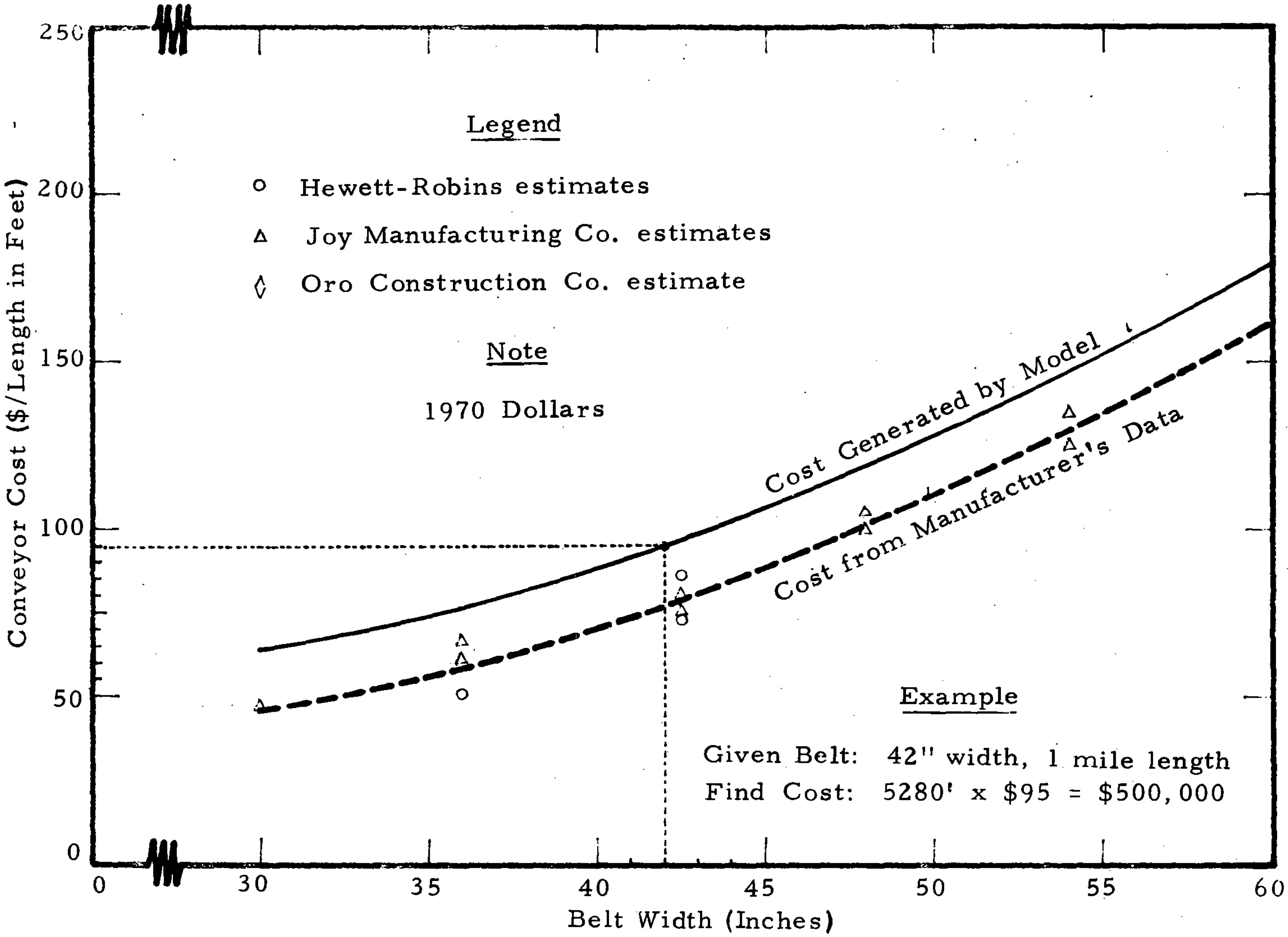

FIGURE 3B-1

CONVEYOR SYSTEM (Horizontal) COST

(Comparison of Conveyor Cost Model and Manufacturer's Data.
Neither curve represents the sum of Figure 3B-2 and 3B-3 curves.)

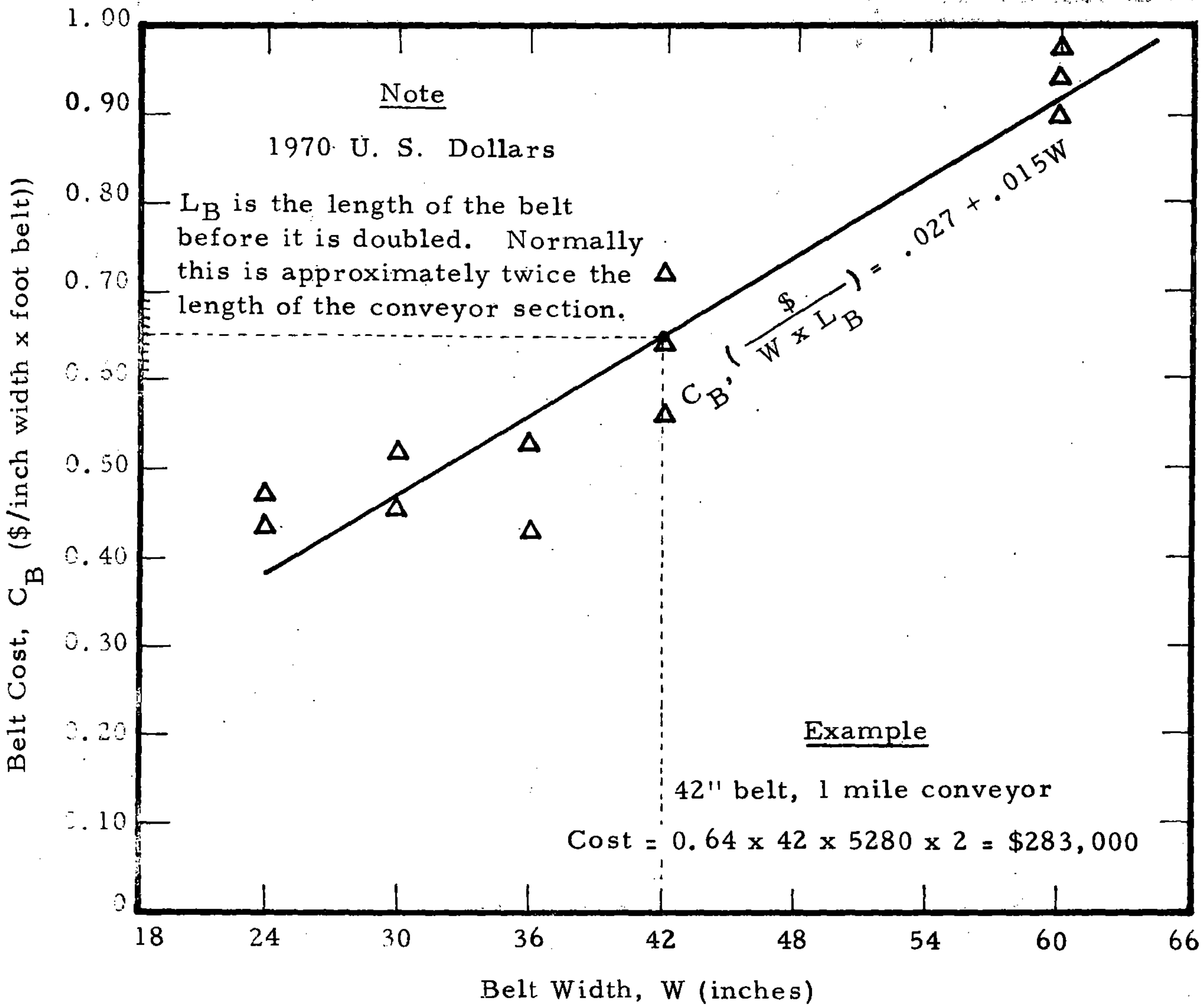

FIGURE 3B-2

CONVEYOR BELT COST

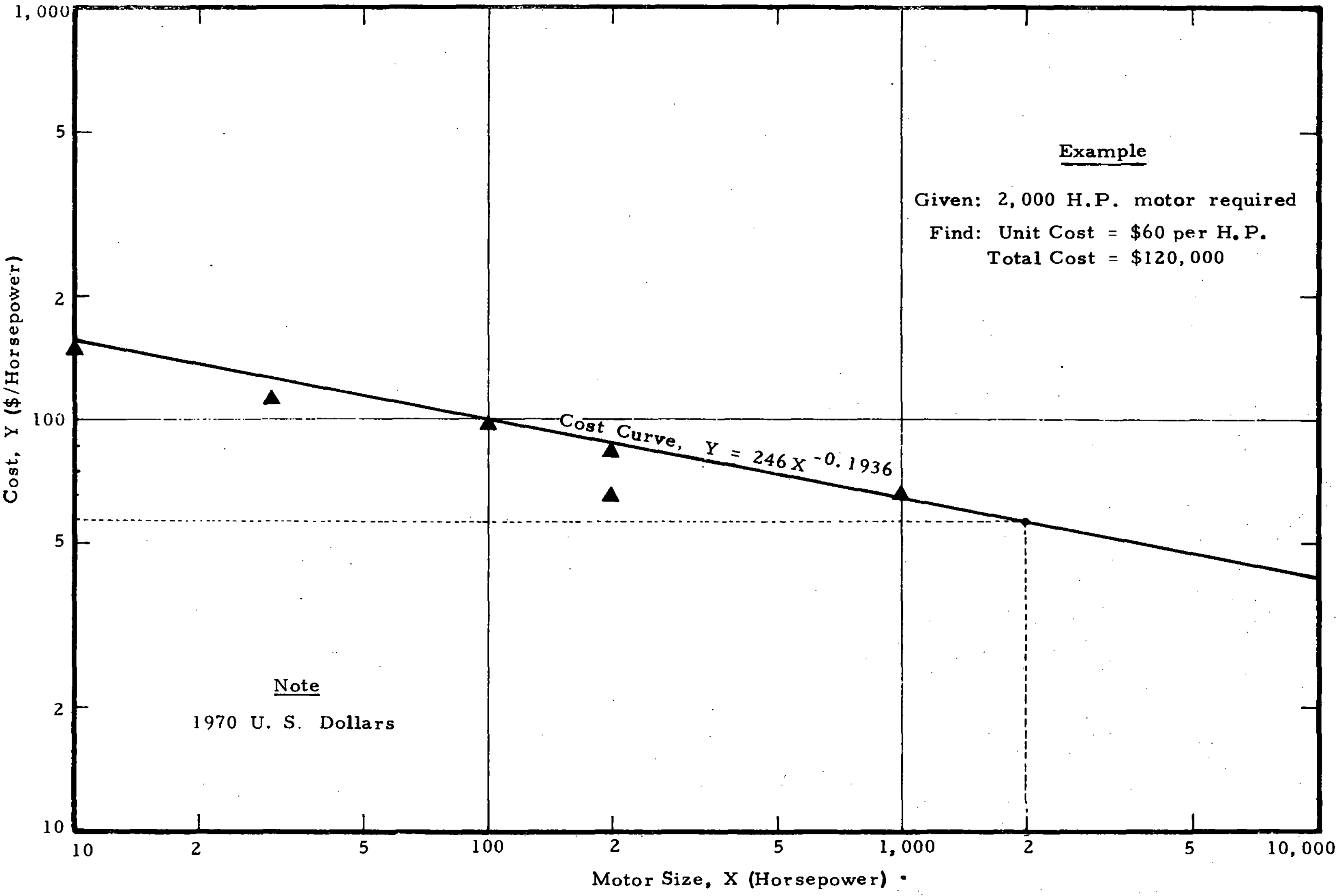

FIGURE 3B-3

COMPOSITE COST FOR MOTORS, GEARBOXES, AND EQUIPMENT

Inclined Segments

The model meets requirements for incline conveyors having a significant vertical lift requirement. This is reflected in higher horsepower requirements and higher belt tensions. In the model, belt costs for inclined sections have been increased by a factor of 1.5[3] corresponding to the increased costs for higher tension belts.

System Cost/Performance

The system cost/performance relationship is represented by the specific cost data presented for two different applications of conveyors in tunnels. These are: Figures 3B-4 and 3B-5, long horizontal flights (up to 1 mile); and Figures 3B-6 and 3B-7, inclined flights used in shafts. The inclined flights are more costly to acquire and operate due to their higher horsepower requirements. Their lengths are limited to 480 feet to limit belt tension. The short segments used for inclined flights are also more costly than the horizontal segments because of the disproportionate use of end equipment. Specific equipment costs can be reduced if higher belt speeds are used. Data is provided for cases where 1.5 x standard belt speeds have been assumed. Operating cost reductions are not attained by using higher belt speeds since the model applies a fixed cost factor ($0.022/cu yd/mi) regardless of speed. In reality, operating costs would probably increase with belt speed.

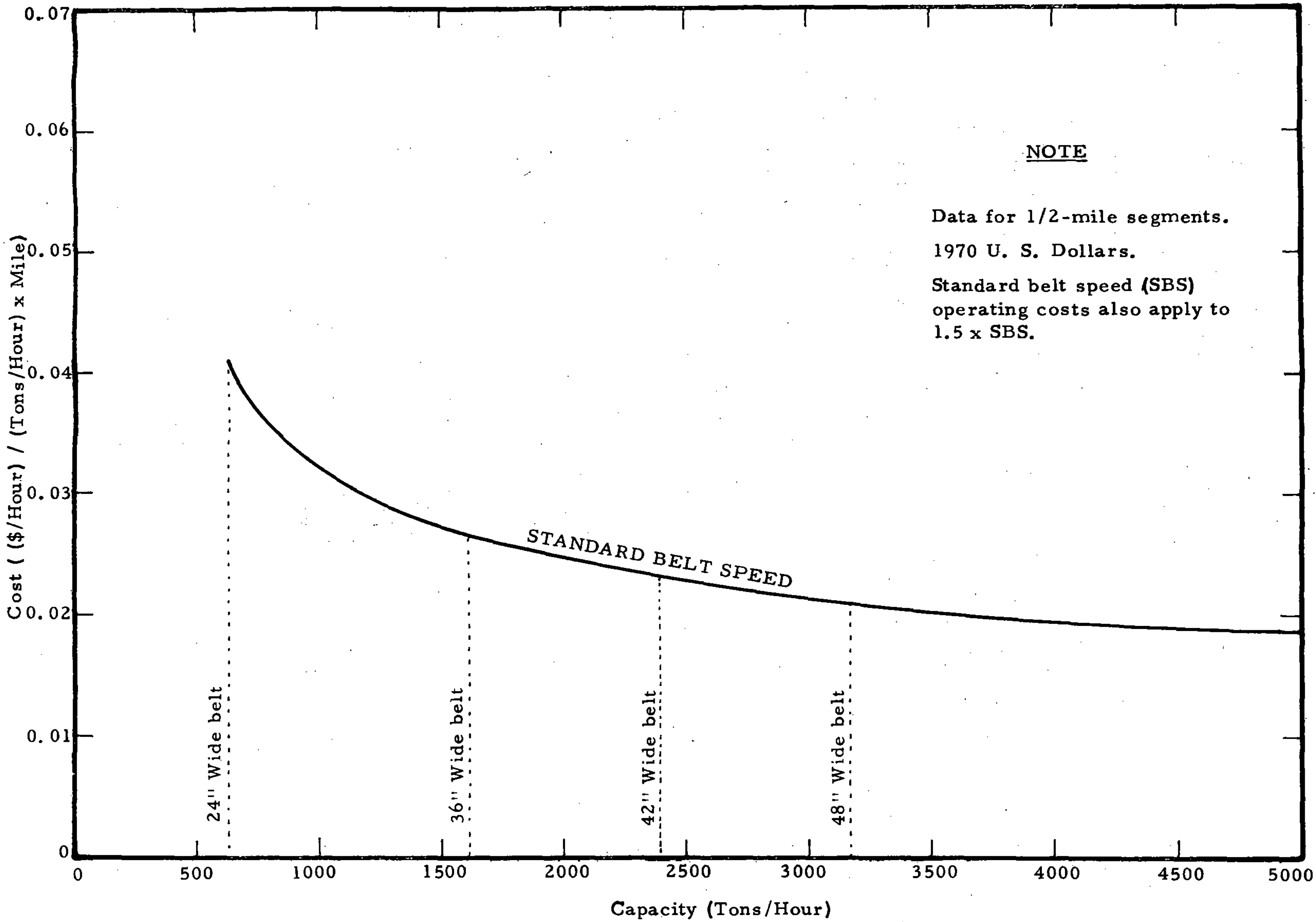

FIGURE 3B-4

LONG CONVEYOR (Horizontal) OPERATING COST

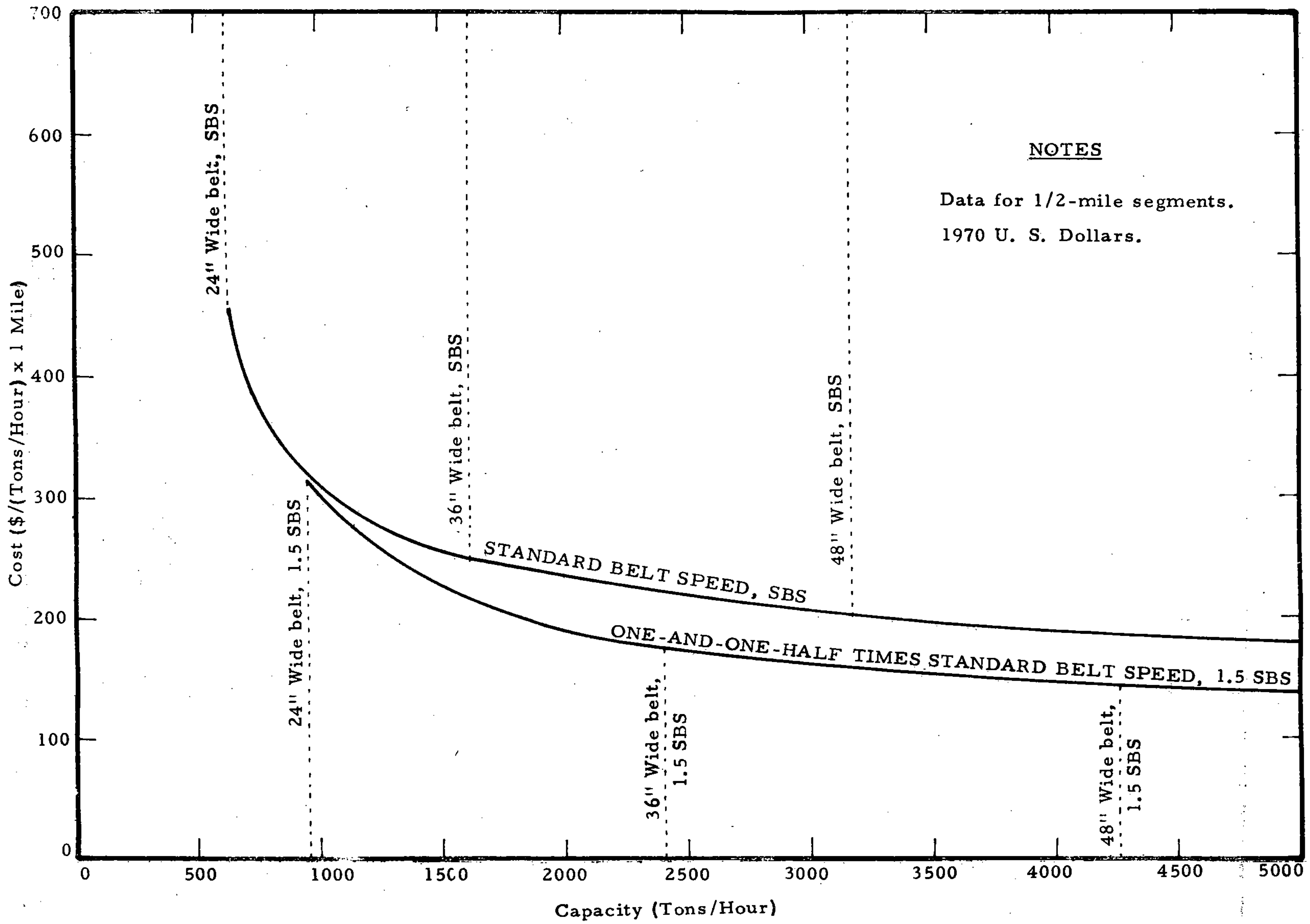

FIGURE 3B-5

LONG CONVEYOR (Horizontal) EQUIPMENT COST

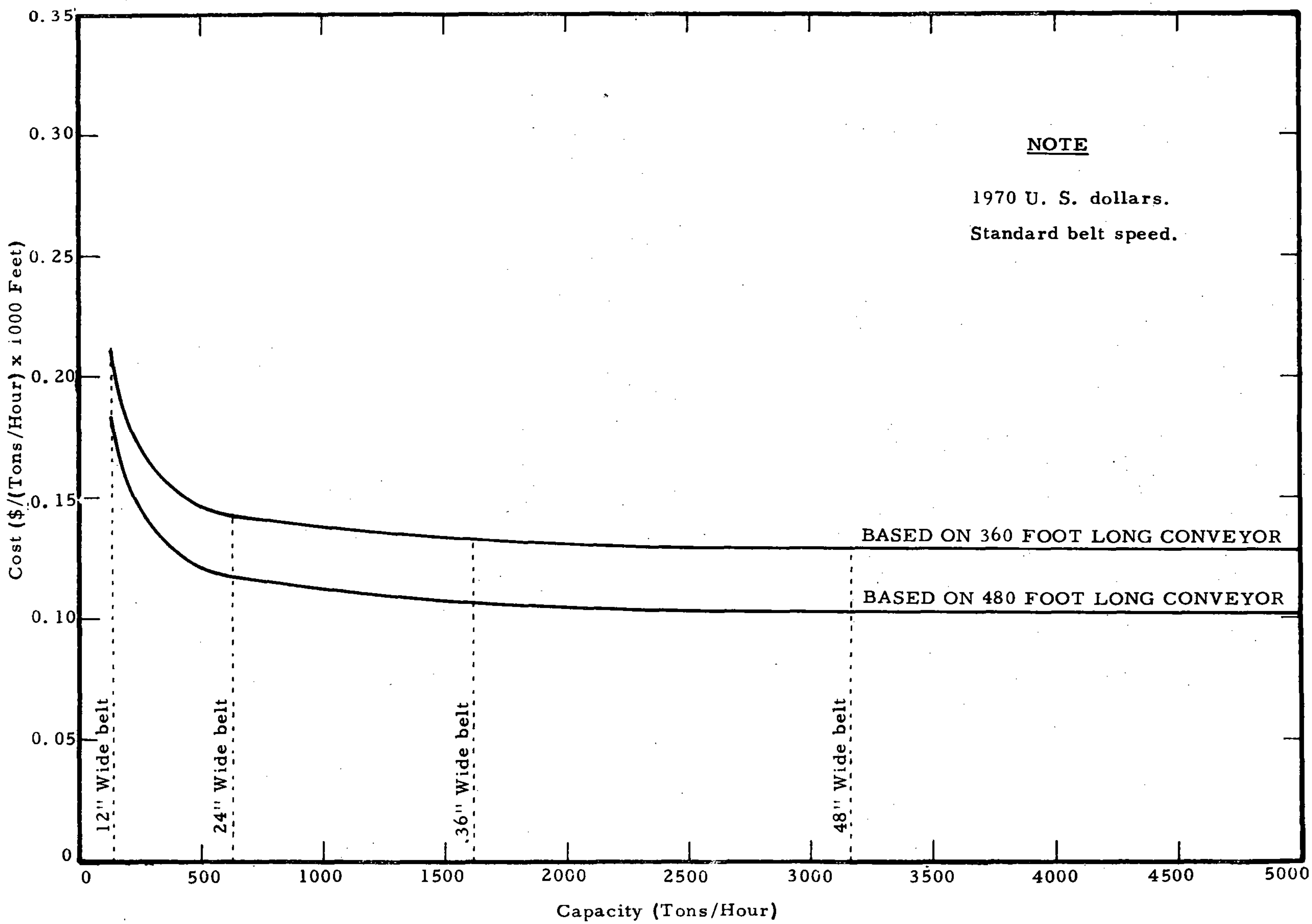

FIGURE 3B-6

SHORT CONVEYOR (Inclined) OPERATING COST

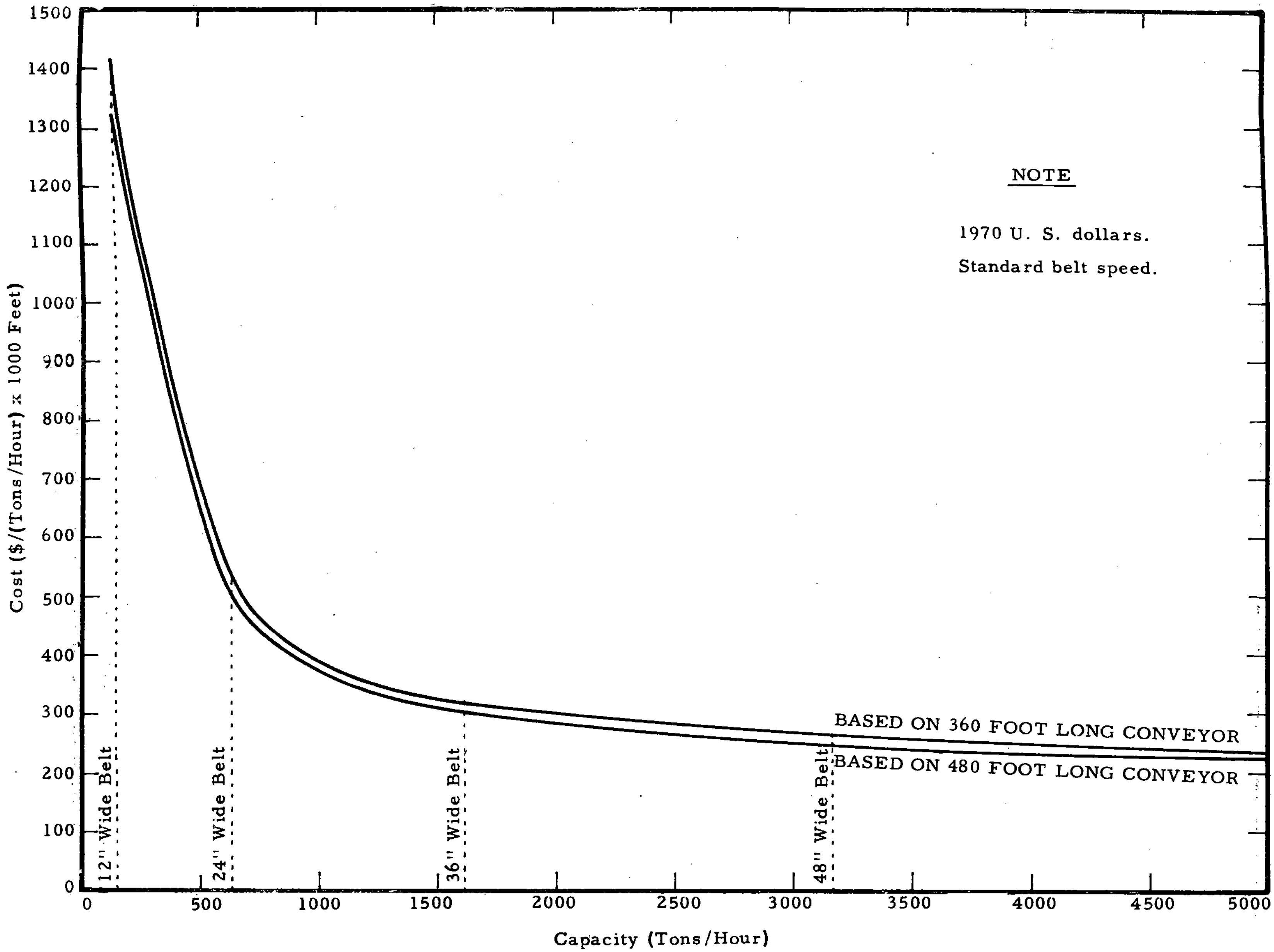

FIGURE 3B-7

SHORT CONVEYOR (Inclined) EQUIPMENT COST

SIDE-WHEEL DRIVE SYSTEM

The side-wheel drive system was chosen as the most representative and adaptable concept of modular type systems. The system is described in Chapter 4. It was not necessary to develop a model for this system since cost/performance relationships were provided in Reference 4 by the manufacturer. Costs for equipment were modified to fit the format of the other system data. Operating cost data were also extracted from this source. These data are presented on Figures 3B-8 and 3B-9 for level systems. The manufacturer also supplied data for a side-wheel drive system operating on a 26 percent slope. These data are presented on Figures 3B-10 and 3B-11. Data for other slopes are not provided, but extrapolations could be made.

It would have been desirable to study the source of this cost performance data in more detail; however, due to the location of the manufacturer and other limitations, this was not practical. The data appeared to be reasonable when compared with other system data and engineering judgment.

PNEUMATIC SYSTEM MODEL

The use of pneumatic systems has long been a primary conveyance method for light weight material, up to and including the density of coal and salt. For conveyance of grain and materials which are light and cannot be wetted, this approach has obvious advantages. Where abrasiveness is not a critical factor, pneumatic systems are extremely flexible; that is, they can negotiate corners and grades and generally do not require a straignt-line course.

Recently, pneumatic conveyance has attracted a degree of attention in the handling of mine or tunnel materials since only air and a pipe is required to transport the materials. The fact that air used in the conveyor system can also double as ventilation air is a positive benefit. Pneumatic conveyances appear, at the present time, to be more costly than other means of conveyance. However, under special circumstances, such as back filling, this extra cost can be tolerated. The compaction and flexibility gained by using a pneumatic system is difficult to attain by alternate means.

From a theoretical point of view, pneumatic system performance is one of the most difficult types of phenomena to describe; and, in fact, very little recent theoretical work has been published in this area. To add to the difficulties encountered in describing a pneumatic system analytically, almost all private concerns involved in promoting pneumatic conveyance concepts are unusually cautious about releasing technical parameters.

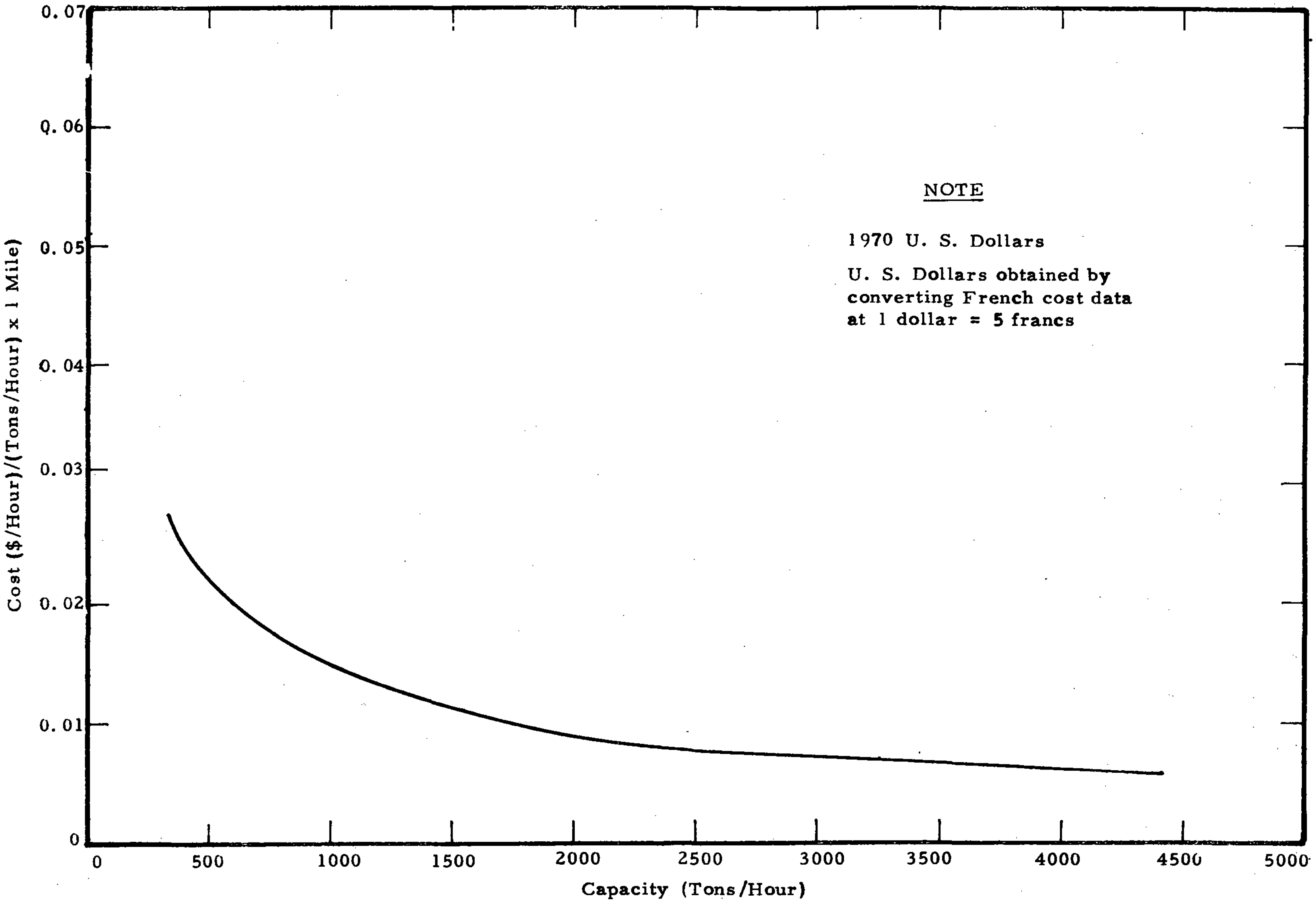

FIGURE 3B-8

SIDE-WHEEL DRIVE (Horizontal) OPERATING COST

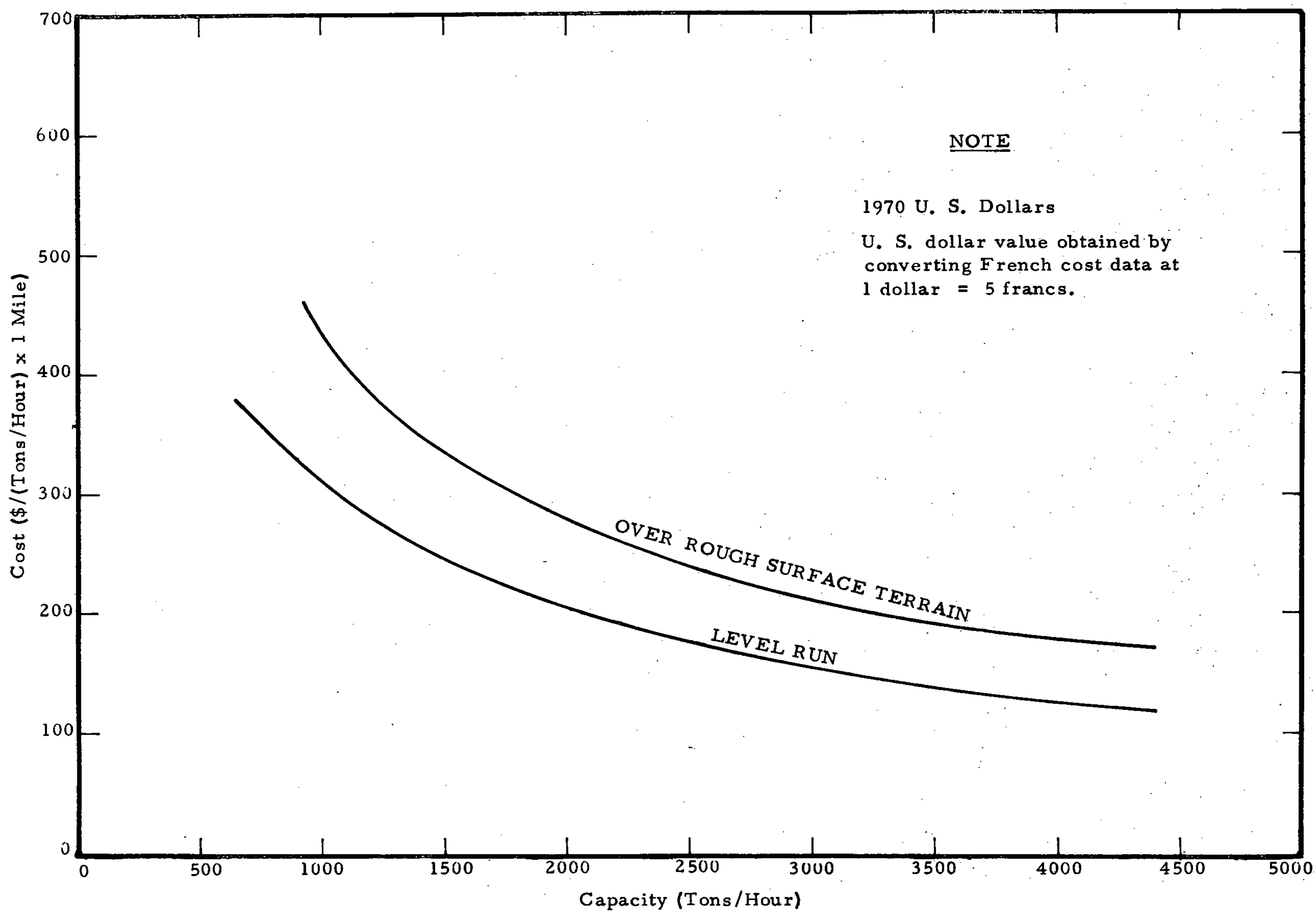

FIGURE 3B-9

SIDE-WHEEL DRIVE (Horizontal) EQUIPMENT COST

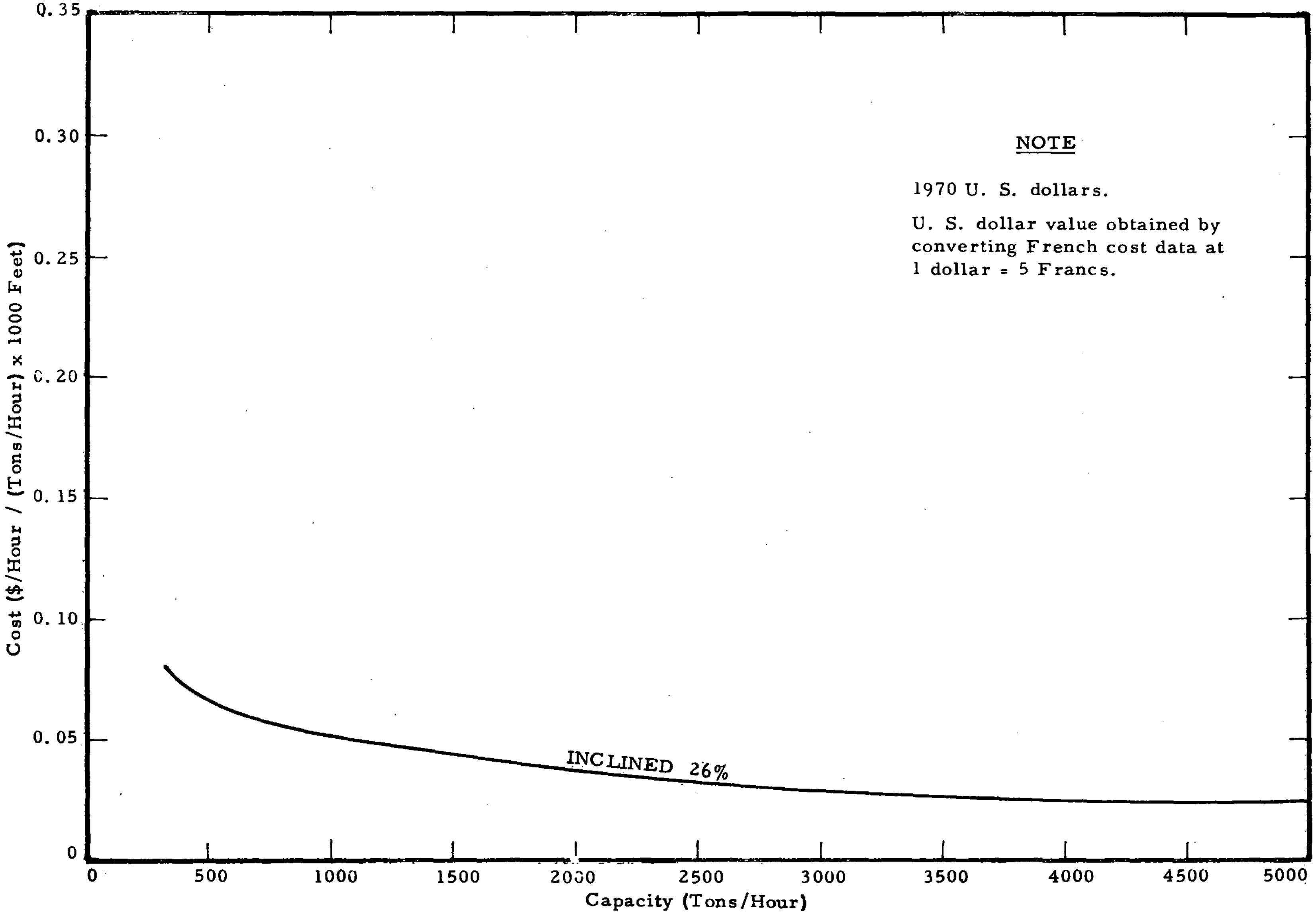

FIGURE 3B-10

SIDE-WHEEL DRIVE (Inclined) OPERATING COST

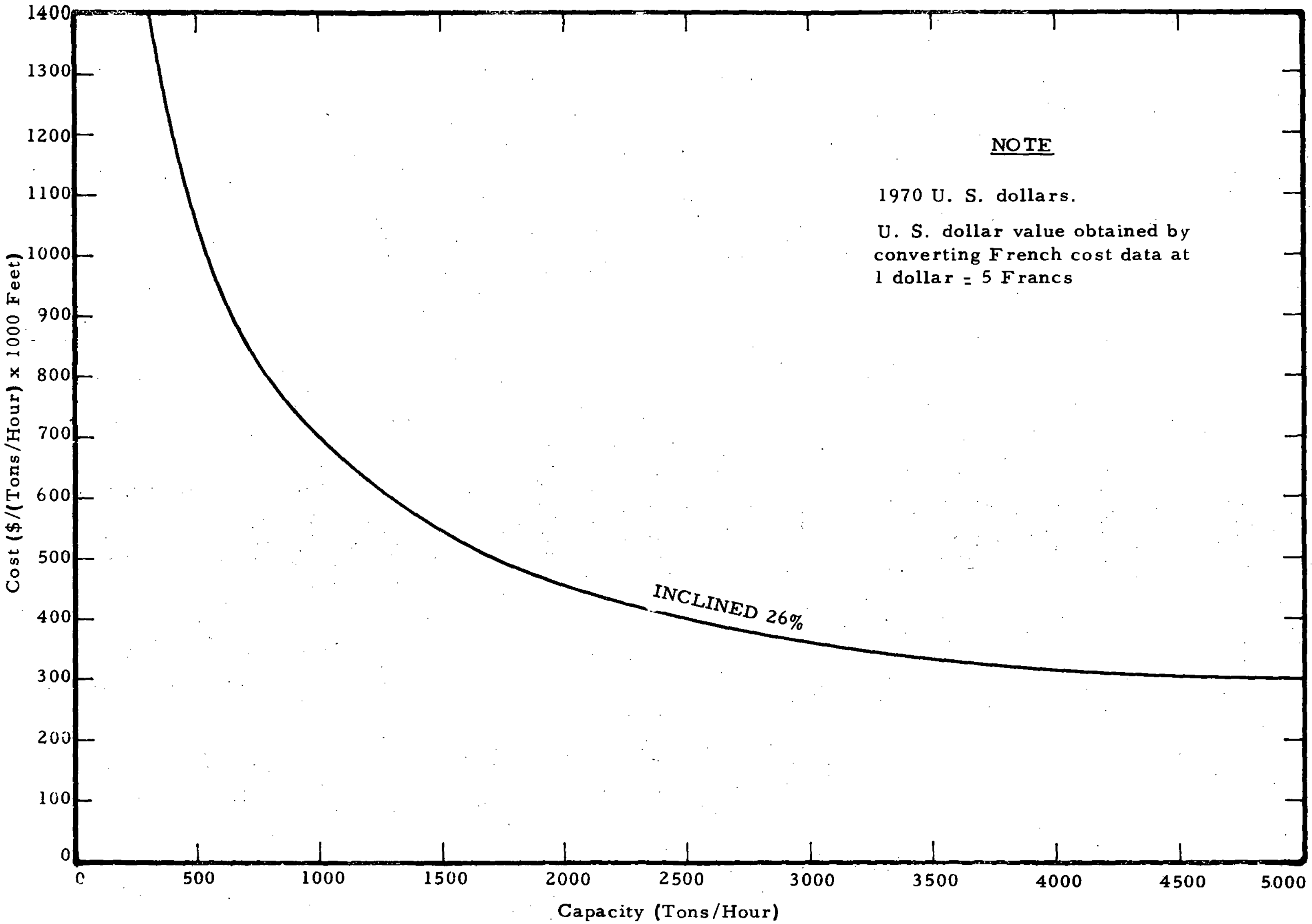

FIGURE 3B-11

SIDE-WHEEL DRIVE (Inclined) EQUIPMENT COST

Using Reference 5, it is possible to describe a system which transports material in 1,000-foot steps. (No examples of pneumatic pipeline experiments longer than 2,000 feet were discovered, and the 2,000-foot example was unsuccessful.) The examples in Reference 5 have the following specifications:

Back Filling

250 Tons per Hour
250-Foot Length
$0.22 per Ton Material Handling Costs

Material Transfer
Operating Costs per Ton-Mile

300-Ton-per-Hour System		1,000-Ton-per-Hour System	
Power	.125	Power	.075
Major Overhaul	.08	Major Overhaul	.020
Pipe Replacement	.60	Pipe Replacement	.100
Labor	.072	Labor	.070
Maintenance	.150	Maintenance	.350
	$1.027		$0.615
Equipment Costs		Equipment Costs	
$400,000 per Mile		$1,200,000 per Mile	

The examples are apparently based on five 1,000-foot segments in series. Power requirements are high compared with other systems. Motor sizes of about 10 horsepower per ton per hour per mile (horizontal) are required for pneumatic systems. Experience indicates that horsepower requirements for vertical lift are about equal to those requirements for horizontal transfer. This is not intended to imply that the system is efficient in vertical lift. On the contrary, it is so inefficient in either horizontal or vertical application that the work accomplished in lifting material is insignificant compared to the total horsepower required. Based on limited information, equipment costs are approximately 10 percent of total material handling costs on a lifetime amortized basis. For a 200-ton-per-hour system, power, labor, pipe, major overhaul, and other maintenance costs are estimated to be $1.08 per ton per mile; and equipment costs are estimated to be $350,000 per mile. Economy of scale factors probably exist for larger systems for both equipment costs and operating costs, but this is not proven. The data available for pneumatic systems are plotted on Figures 3B-12, 3B-13, 3B-14, and 3B-15.

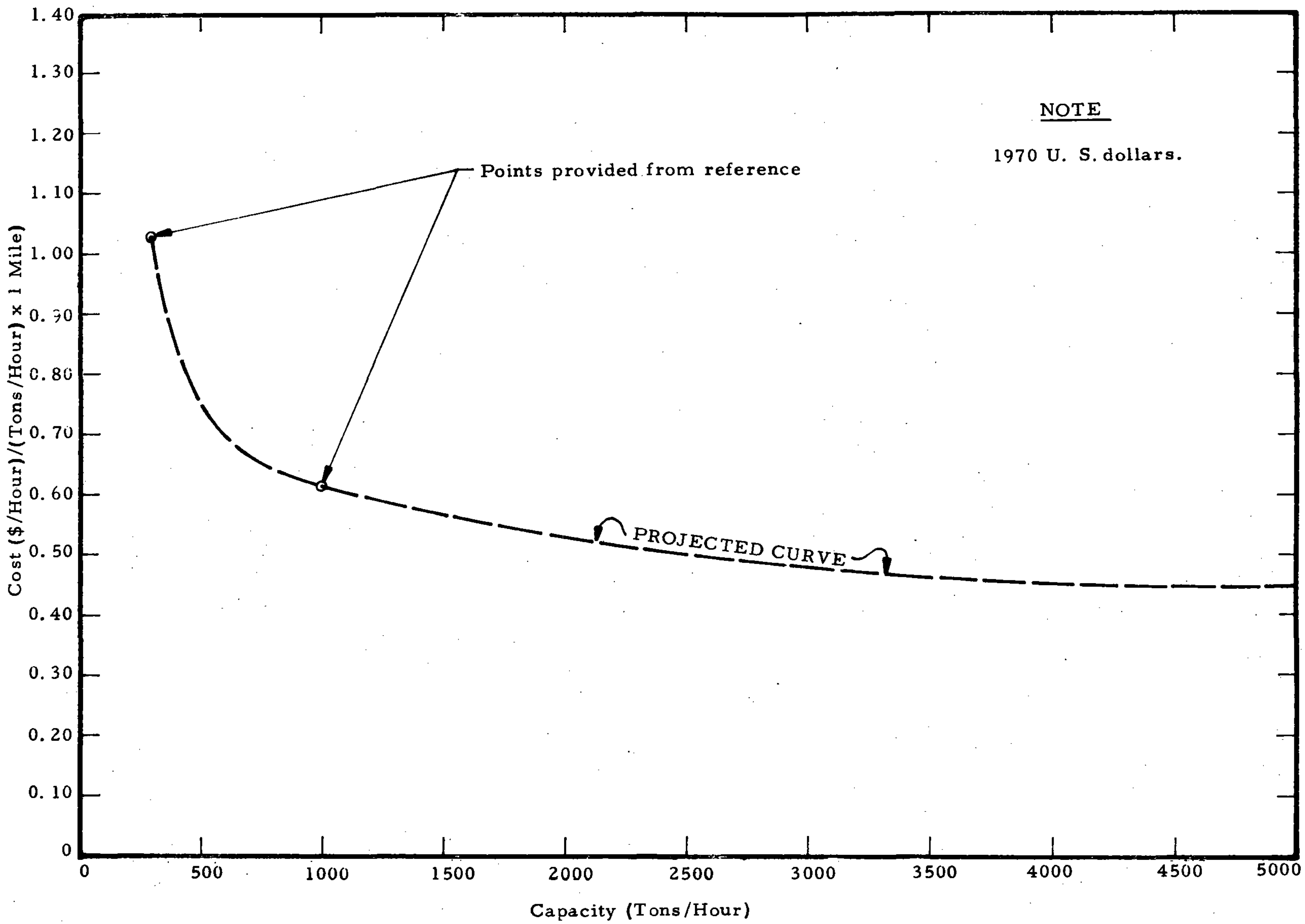

FIGURE 3B-12

PNEUMATIC SYSTEM (Horizontal) OPERATING COST

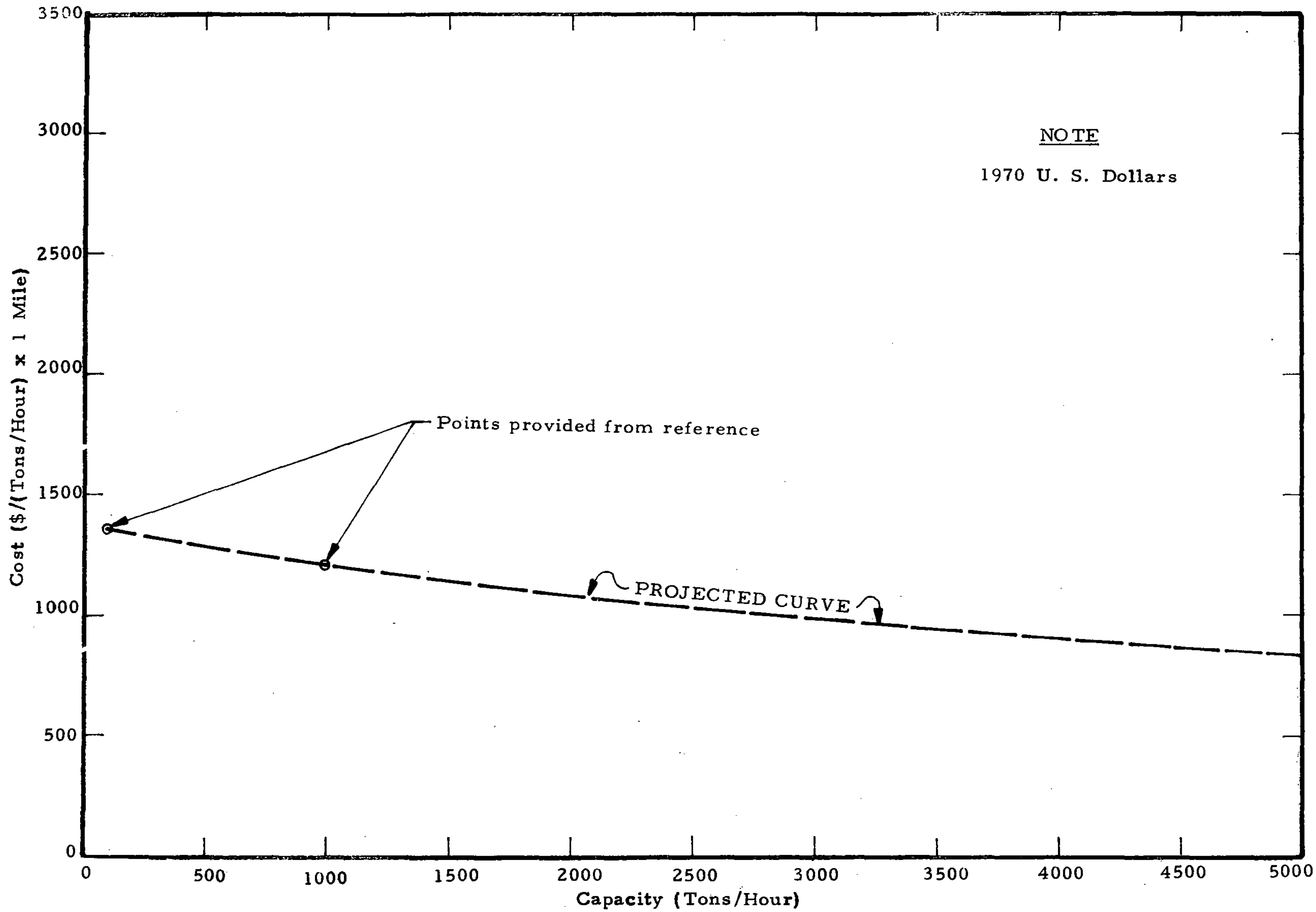

FIGURE 3B-13

PNEUMATIC SYSTEM (Horizontal) EQUIPMENT COST

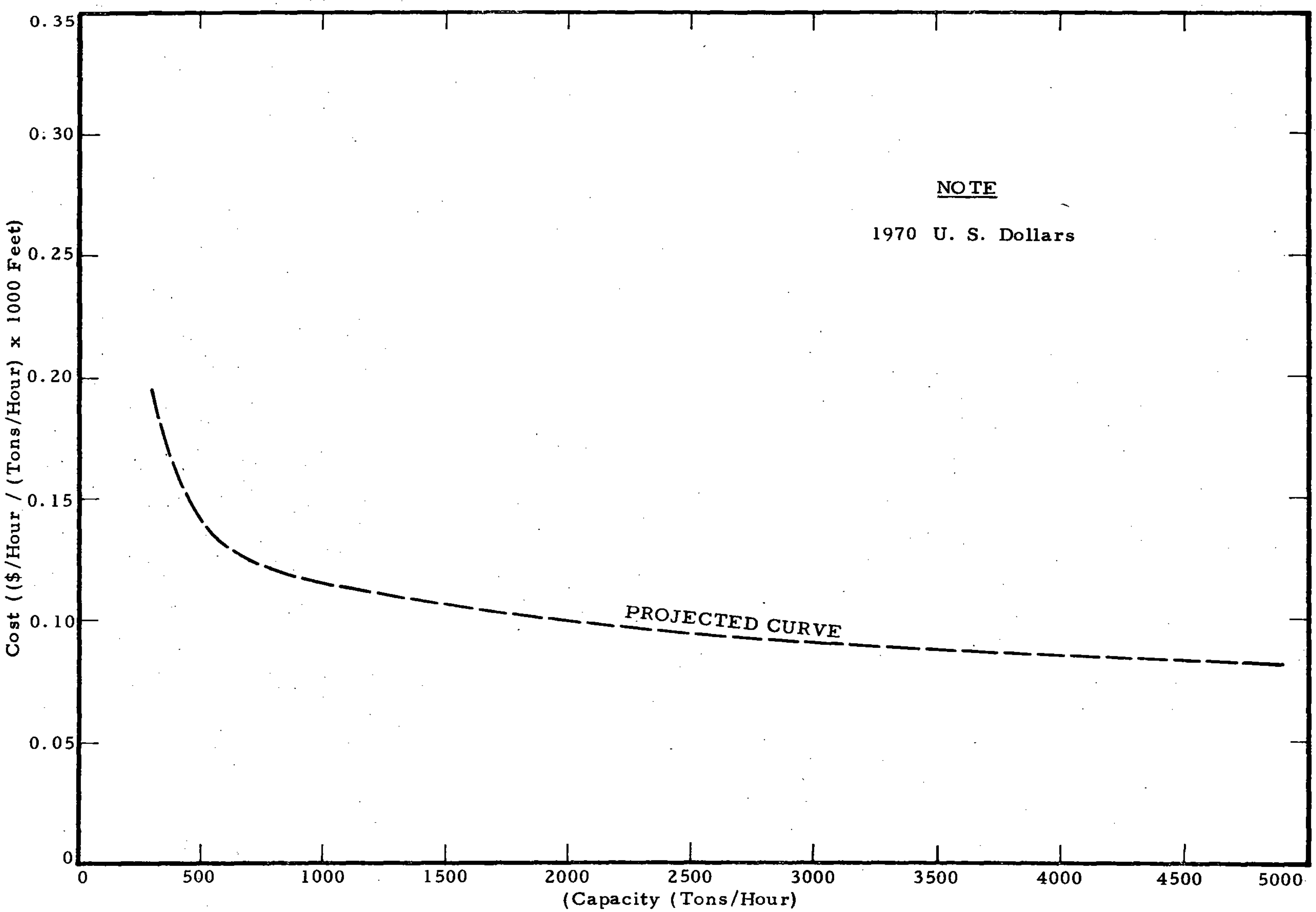

FIGURE 3B-14

PNEUMATIC SYSTEM (Vertical) OPERATING COST

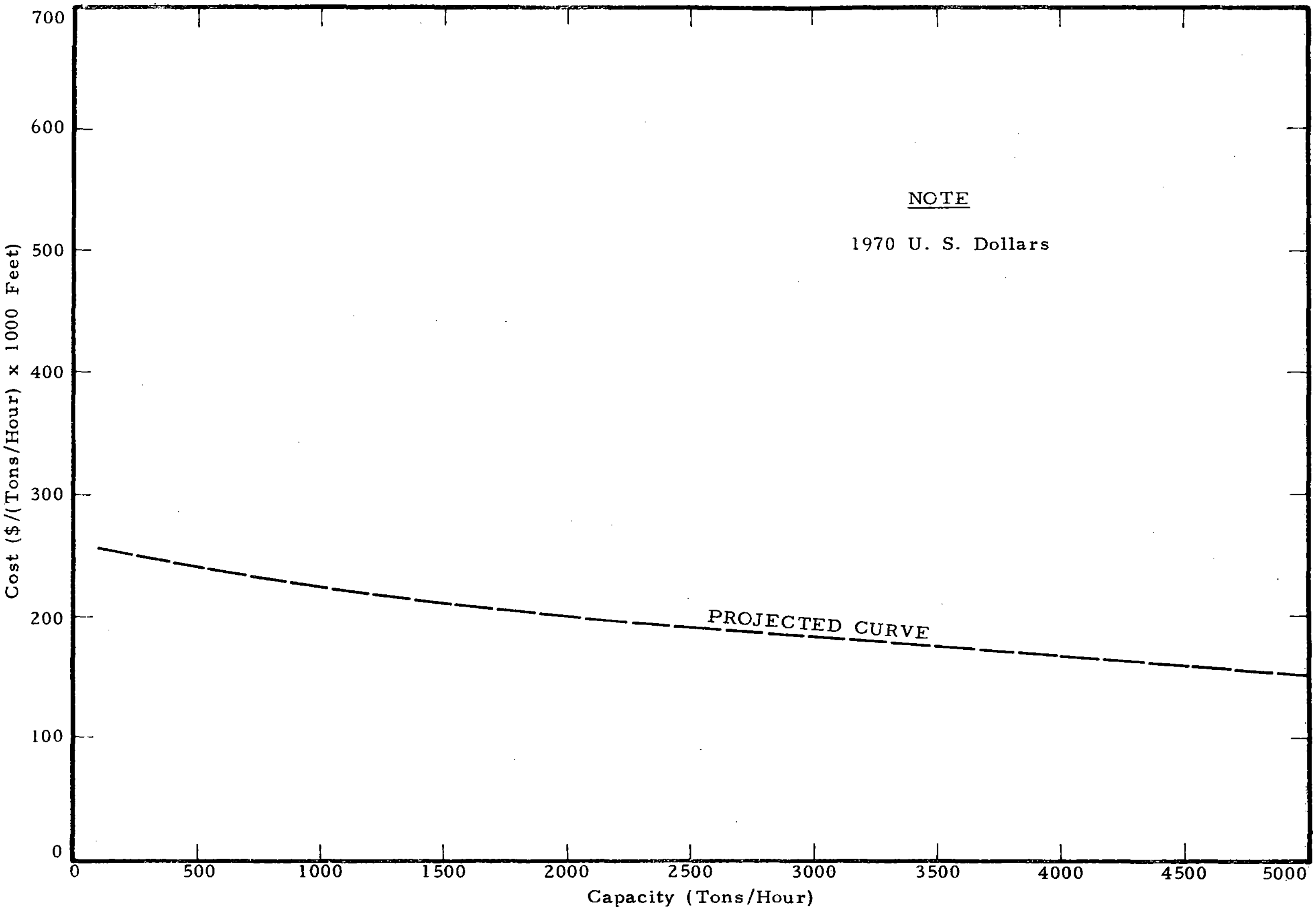

FIGURE 3B-15

PNEUMATIC SYSTEM (Vertical) EQUIPMENT COST

One important characteristic of pneumatic systems is their ability to use a small opening to the surface to dispose of the muck. Exploratory holes, for example, could be utilized. If these are drilled every 1/4 mile, the total horizontal distance for muck movement can be limited to this distance provided a muck disposal site is available at the shaft collar. Under these conditions the cost per mile may be high, but the number of miles is fractional, thereby giving this system a great deal of cost leverage. Lifting vertically can be accomplished, but the overall lift height is probably limited to less than 1,000 feet per system segment. Pipe sizes required for the pneumatic systems are as follows:

300 tons per hour	14-inch diameter
1,000 tons per hour	25-inch diameter

TRUCK SYSTEM

Performance

The truck system performance model was formulated on the performance of contemporary off-road dump trucks, although this design would not be used in its present configuration in future, high advance rate, tunnel projects. Cost increases were included to cover redesign and expansion of capabilities. For example, the following capabilities would be required for trucks used in the high advance rate tunneling situations projected by this report.

1. Decreased height and width (appearance would be more like a gondola car with tires on each end).

2. Bidirectional steering and drive capabilities.

3. Side or bottom dump capability.

The acceleration, top speed, horsepower, tire wear, fuel consumption, and maintenance requirements were assumed to be similar to existing trucks of like capacity. Using these basic assumptions, it was possible to model the horizontal material handling system using the further assumption that the trucks would operate at full speed and load and that the tunnel run was level. The modeling approach was simplified to adequately relate the systems capabilities and costs using manufacturer-supplied data.

The following characteristics were defined:

$T_{\ell a}$ = time to accelerate loaded;

T_{ua} = time to accelerate unloaded;

V_{ℓ} = velocity, loaded; and

V_{u} = velocity, unloaded.

The following accelerations were then computed:

$A_1 = V_{\ell}/T_{\ell a}$

$A_2 = V_u/T_{ua}$

The distances required to accelerate and decelerate were computed, assuming in computations that the time to brake is equal to the time to accelerate:

$L_1 = 1/2\ A_1(T_{\ell a})^2$

$L_2 = 1/2\ A_2(T_{ua})^2$

The time to travel in the tunnel at top speed is computed:

$T_{v\ell} = (L - 2 \times L_1)/V_{\ell}$ where L = length of tunel segment.

$T_{v\ell}$ = time at top velocity, loaded

$T_{vu} = (L - 2 \times L_2)/V_u$

T_{vu} = time at top velocity, unloaded.

The cycle time for each truck was then computed based on an assumed unloading time, T_u:

$T = 2T_{\ell a} + 2T_{ua} + T_{v\ell} + T_{vu} + T_u + T_{\ell}$

T = cycle time.

The loading time, T_ℓ, is not specified, but assuming one truck is always in the loading zone, the time to load is

$$T_\ell = \frac{2T_{\ell a} + 2T_{ua} + T_{v\ell} + T_{vu} + T_u}{(N - 1)}$$

where N is the number of trucks in the system.

The system capacity can now be computed as follows:

$$Q = \frac{N \times C(27)(\rho s)(3600)}{T_\ell \; 2000}$$

where

Q = the system capacity in tons per hour,

C = the truck capacity in cubic yards, and

ρs = material density in pounds per cubic foot after swell factor is applied.

T = loading time in seconds.

Cost

The system cost model is developed in two parts: equipment cost and hourly operating cost.

Equipment Costs - Equipment costs are based on the expression

$$(\$) = 1000 \times 1.135 \times 20.08 \times e^{(0.0423C)} \times 1.5$$

Figure 3B-16 shows the development of this expression.

In addition, road preparation in the tunnel can cost from zero for best conditions in a horseshoe or straightwall tunnel to $20 per foot of road with unfavorable conditions. These costs are not included in the system model, but various assumed conditions are examined with the integrated model.

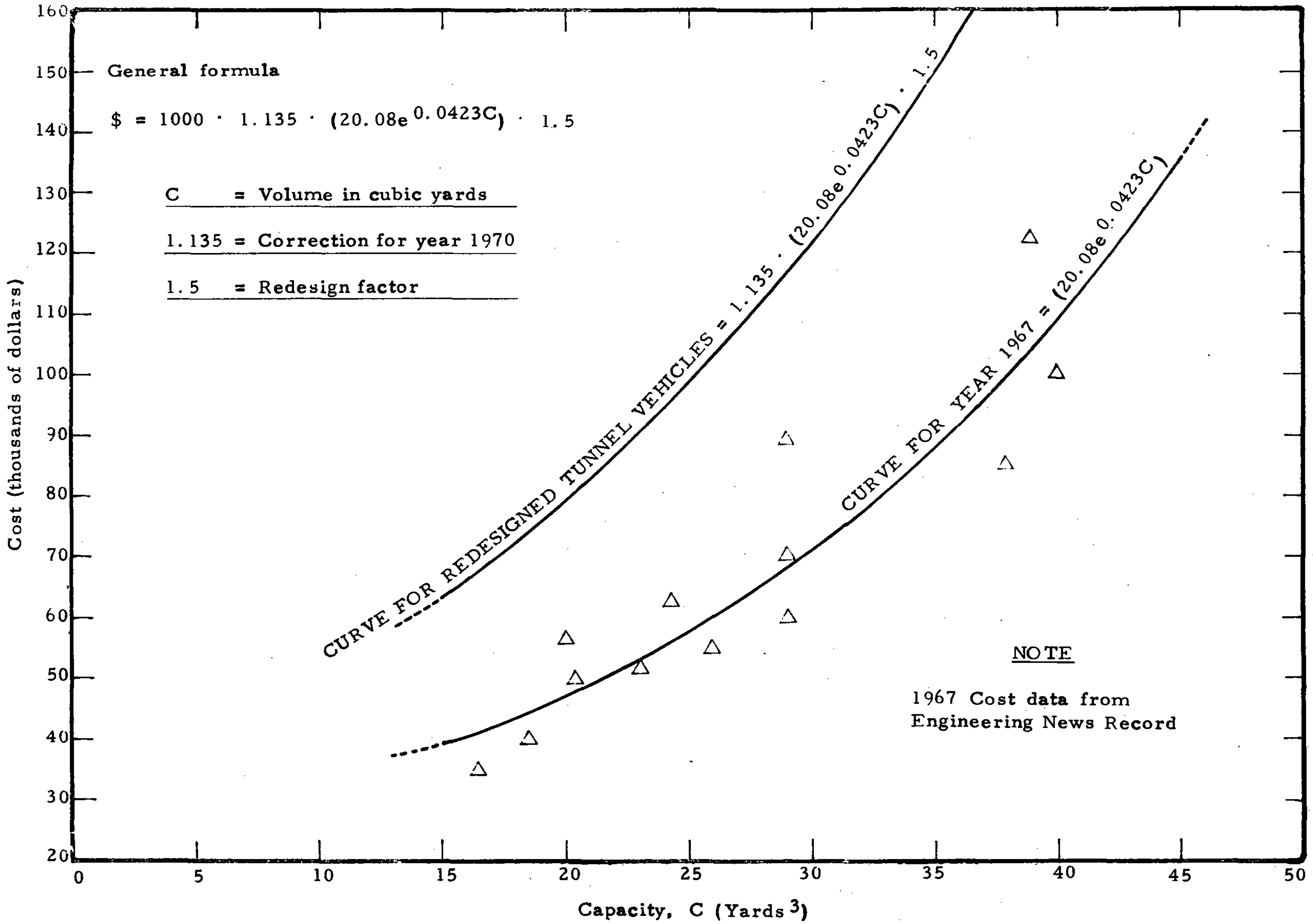

FIGURE 3B-16

TRUCK VEHICLE COST

Operating Costs - The hourly operating costs are based on the summation of the following cost elements derived from Figure 3B-17.

Operator cost,
Fuel cost,
Tire cost,
Repair cost.

Operator costs, based on one operator per vehicle are

$$(\$/Hr) = 7.75 \times N$$

Fuel costs based on Reference 6 and Reference 7 are roughly proportional to the vehicle size and horsepower. For this application:

$$(\$/Hr) = C(0.07)\ N$$

Tire costs, based on data from Reference 7 and manufacturer's data suggests a tire life of 2,100 hours as being reasonable for tunnel surface.

$$(\$/Hr) = (C - 4)\ N \times 0.28$$

Repair costs are given by the expression

$$(\$/Hr) = (C - 5.5)\ N \times 0.1333$$

These costs check with the rule of thumb offered by Reference 7; i.e., repair costs for large trucks are equal to 0.8 times the hourly depreciation costs of the truck depreciated over 15,000 hours. Operating costs are the sum of these cost elements.

System Cost/Performance

Figures 3B-18 and 3B-19 represent the operating and equipment cost/performance characteristics for truck systems. Note that an increase in truck speed decreases the costs significantly, but the speed at which drivers can traverse the tunnel is a trade-off between roadbed preparation, steering aids, and driver adaptation and willingness. These trade-offs could not be assessed.

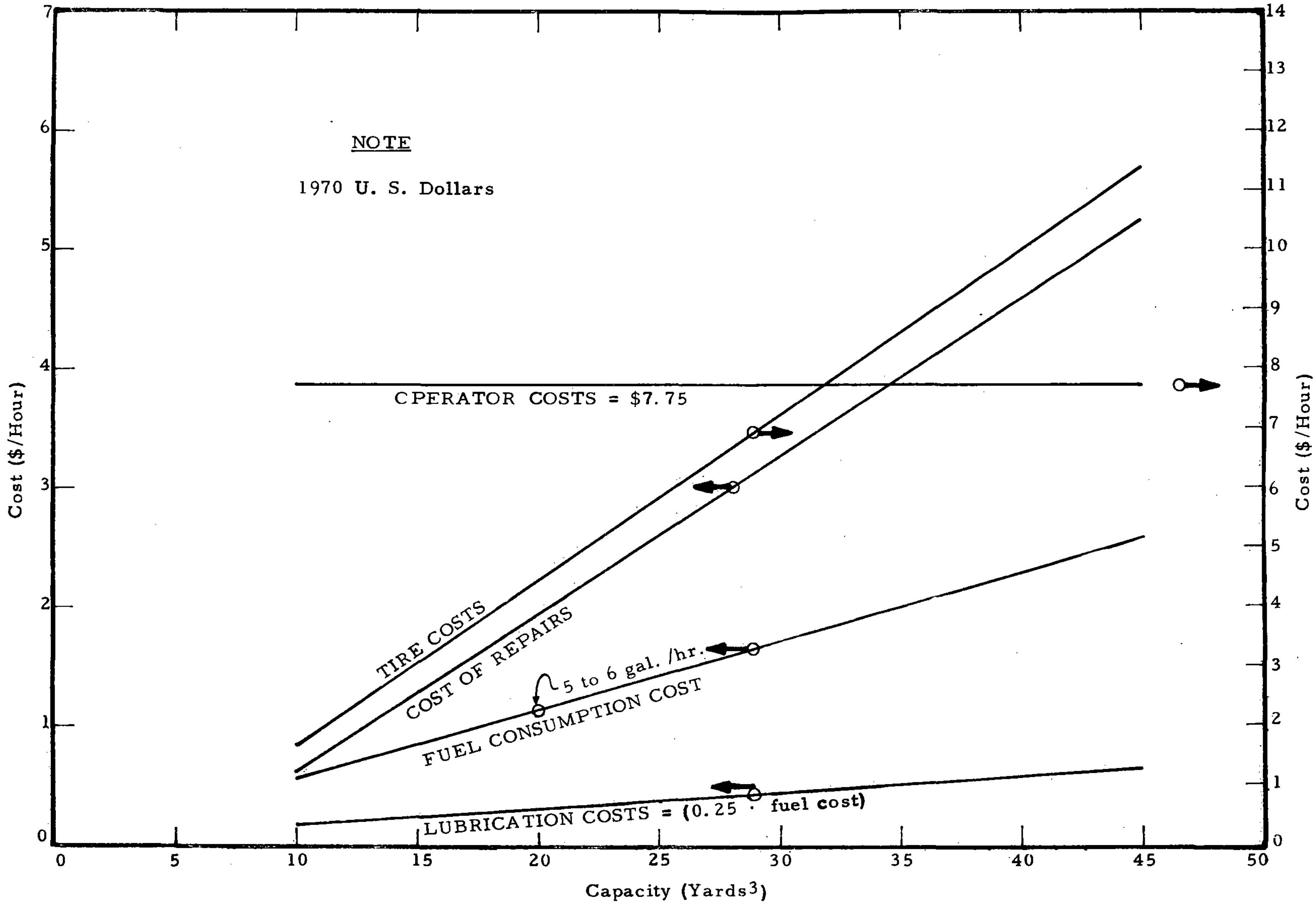

FIGURE 3B-17

TRUCK OPERATING COST ELEMENTS

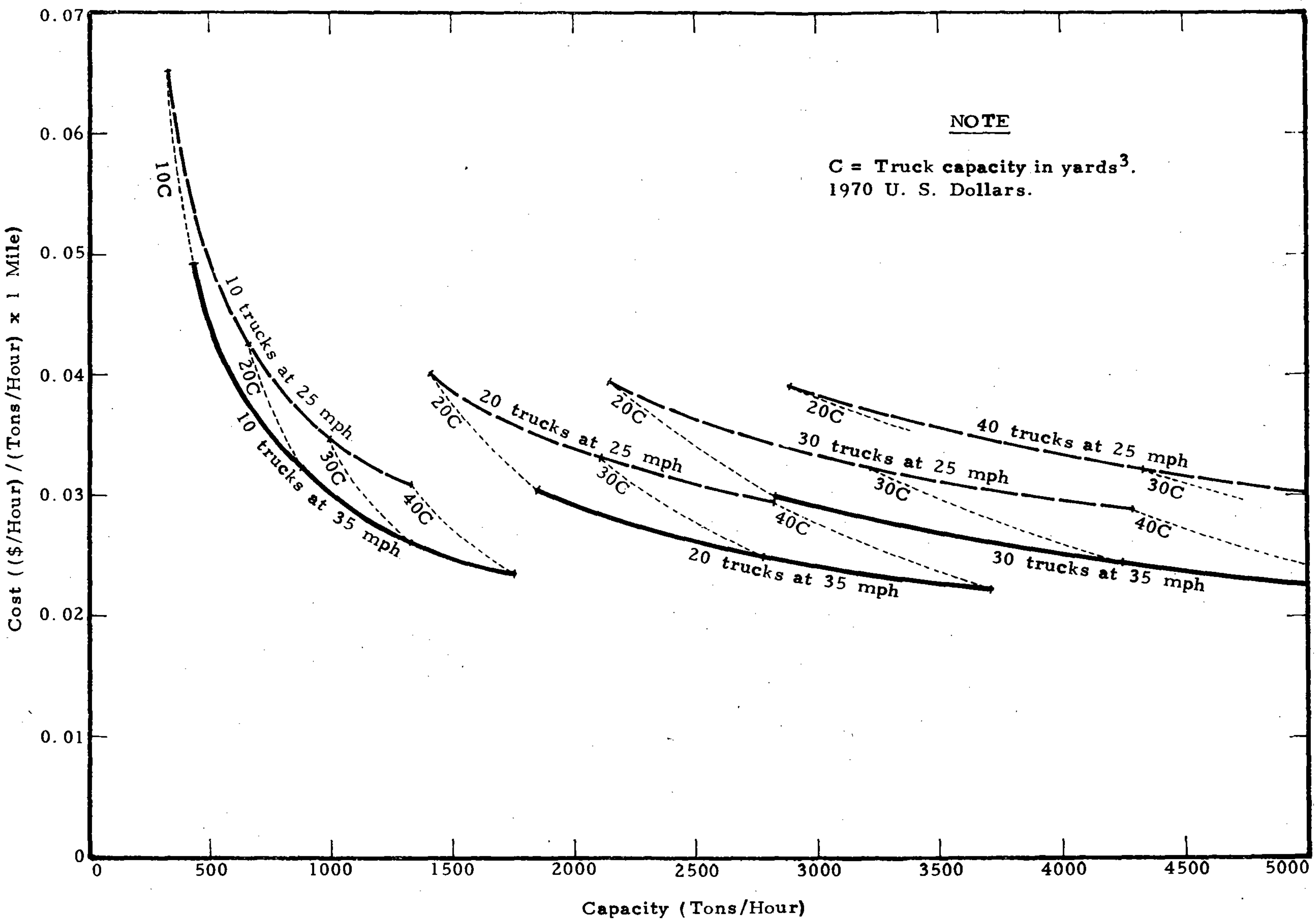

FIGURE 3B-18

TRUCK SYSTEM OPERATING COST

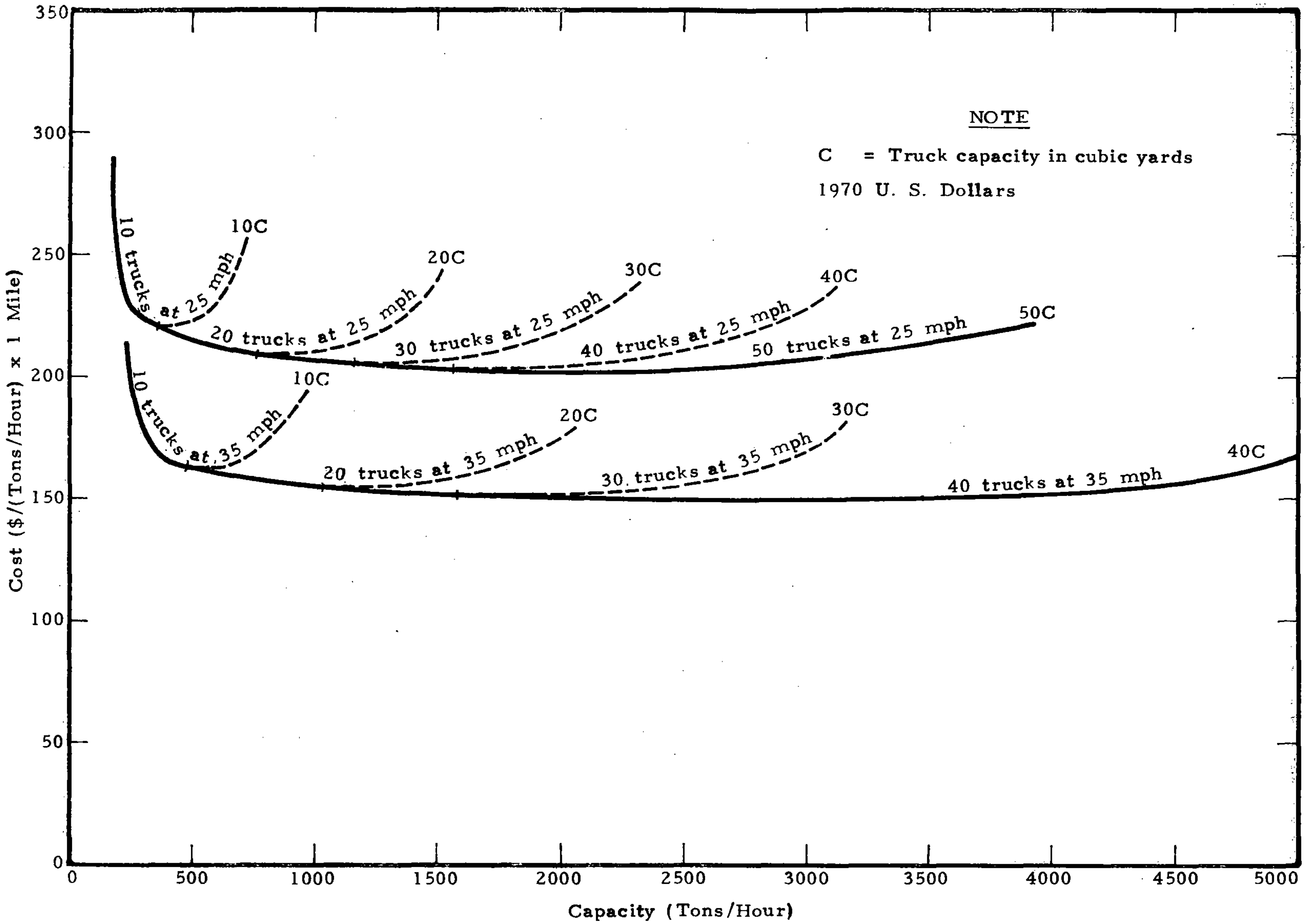

FIGURE 3B-19

TRUCK SYSTEM EQUIPMENT COST

SIDERAIL SYSTEM (Horizontal)

Performance

The model used to compute the performance of siderail systems is basically the rubber-tired vehicle model, which defines acceleration times, top speeds, and unloading time. From these factors and the length of the run, cycle time and system capacity are computed for various numbers of cars. Based on the characteristics of contemporary models, the specific investment cost for this type of system appears to be high due to both the cost of individually powered modules and structural steel track. In order to expand capacity of the basic system, the computer program was used to increase the number of modules while keeping the number of power units constant. In this way, the cost performance changes required for this type of system to keep it competitive with larger capacity systems were studied.

A fairly optimistic set of speed conditions for the system was assumed purposely to keep the required number of relatively expensive modules low. These conditions are:

	Loaded	Unloaded
Top Speed	40 mph	60 mph
Acceleration Time	1 min	0.5 min
Time to Unload	1 min	

Cost

The basic cost of the modules is estimated to be $5,000 each in production quantities of several thousand, although there is some indication that actual costs might be as high as $8,000. The $5,000 cost was arrived at by estimating the cost of the various components such as gearboxes, motors, module frame, and container.

Motors - A very conservative estimate of motor costs can be arrived at by using a $33 per horsepower cost figure for smaller, squirrel-cage rotary, 3-phase, 60-cycle motors of slip-proof design. Since the module being studied includes two 15-horsepower units, total motor costs are estimated to be $1,000. This figure is conservative in that large, high speed, rotary induction motors typically used in traction devices cost about $36 per horsepower; smaller units are certain to cost more.

Gearboxes - The system uses a precision high reduction gearbox with two high torque outputs. It is expected to have an aluminum housing and high tolerance bearings. Two gearboxes with a design horsepower rating of 60 horsepower each were assumed for ruggedness and long life. Gear manufacturers estimate that a typical industrial gearbox of this design would cost about $1,400 in production quantities. Each module requires two gearboxes; thus, for each module, the total is $2,800.

This is a conservative figure, since traction gearboxes for trains are among the most expensive of all types of gearboxes. For high-speed trains, the comparison with helicopter gearboxes is sometimes made. As a rough example, a 1,000-pound gearbox for helicopters would cost approximately $90,000.

Carriage and Container - Based on weight and structural design, a cost of $1,200 is added for the remainder of the module components. The total module cost is as follows:

Motors	$1,000
Gearboxes	2,800
Carriage	1,200
	$5,000

Another element of conservatism in the cost is attained by not including the control system cost.

Track - An estimate of the track cost for a siderail installation at the White Pine Copper Mine in White Pine, Michigan, serves as a baseline for this estimate. Reference 8 indicates in a news item that the track costs for this installation are as follows: "Exclusive of controls and modules, it is expected to cost $2. 5 million or approximately $500,000 per mile." This is about $95 per foot at 1968 dollars.

A check of structural steel quantities used for the track system indicated that about 105 pounds of structural steel per foot of track was used on a single track, and double that for a double track. Since the configuration of the steel structure is relatively simple, it seemed inappropriate to apply the prevailing labor costs for installing structural steel, particularly since this would have resulted in higher costs than those quoted. By combining the rail support with the tunnel support system, a cost per foot of $78 was arrived at for a single-track system (corresponding to $0. 75 per pound installed cost). In this system model, $42. 50 per foot of this cost appears as material and prefabrication costs; and the remainder is included as costs for system extension labor in the integrated system model.

Cost Estimating Relationships - CERs used in the system performance model are as follows:

Equipment - Initial Cost

$$\$ = 5{,}000N + L \times 42.5 \times 5{,}280 \times K$$

Single Track, $K = 1$
Double Track, $K = 2$

Maintenance and Operation - Labor Cost

$$\$/hr = 2 \times L \times 6.45 + \left(\frac{N}{20}\right) \times 9.75 + 3 \times 7.88$$

Track Crew Wage	Master Mechanics Wage	Maintenance Wage

Maintenance Parts Cost

$$\$/hr = 0.002 \times 50 \times N + 0.0005\,(300)N$$

Tire Cost*	Container Cost**

*Tire cost based on four tires per vehicle, 2,000-hour life, $50 per tire replacement cost.

**Container cost based on 2,000-hour life, $300 replacement cost.

Energy Cost

$$\$/hr = 30 \times 0.015 \times N$$

System Cost/Performance

Figures 3B-20 and 3B-21 present specific operating and equipment costs for the horizontal siderail system. For larger system capacities, the number of modules is increased for each drive unit to achieve better economy. A larger single module could be used in lieu of increasing the number of modules if this is compatible with tunnel space limitations.

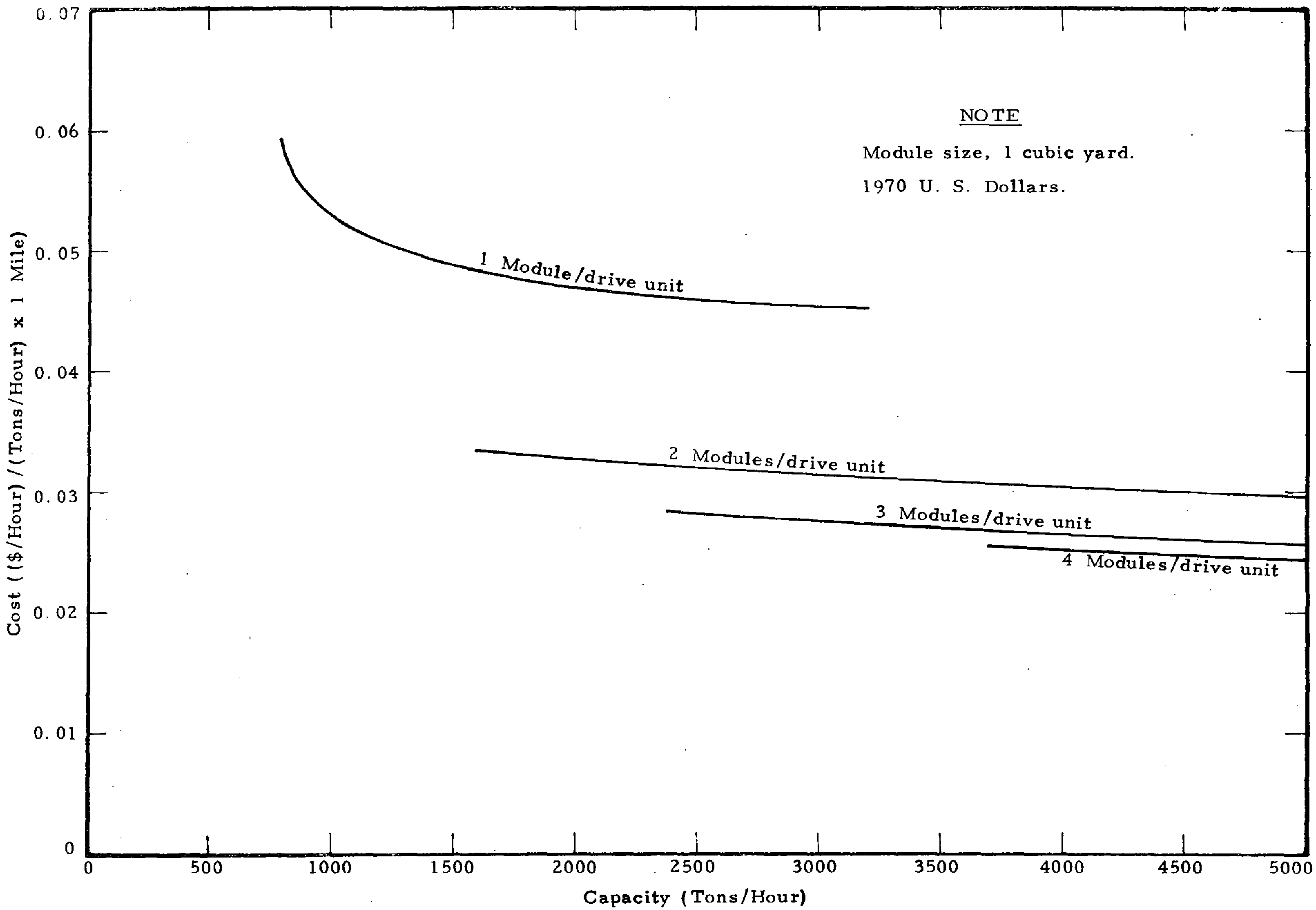

FIGURE 3B-20

SIDERAIL SYSTEM (Horizontal) OPERATING COST

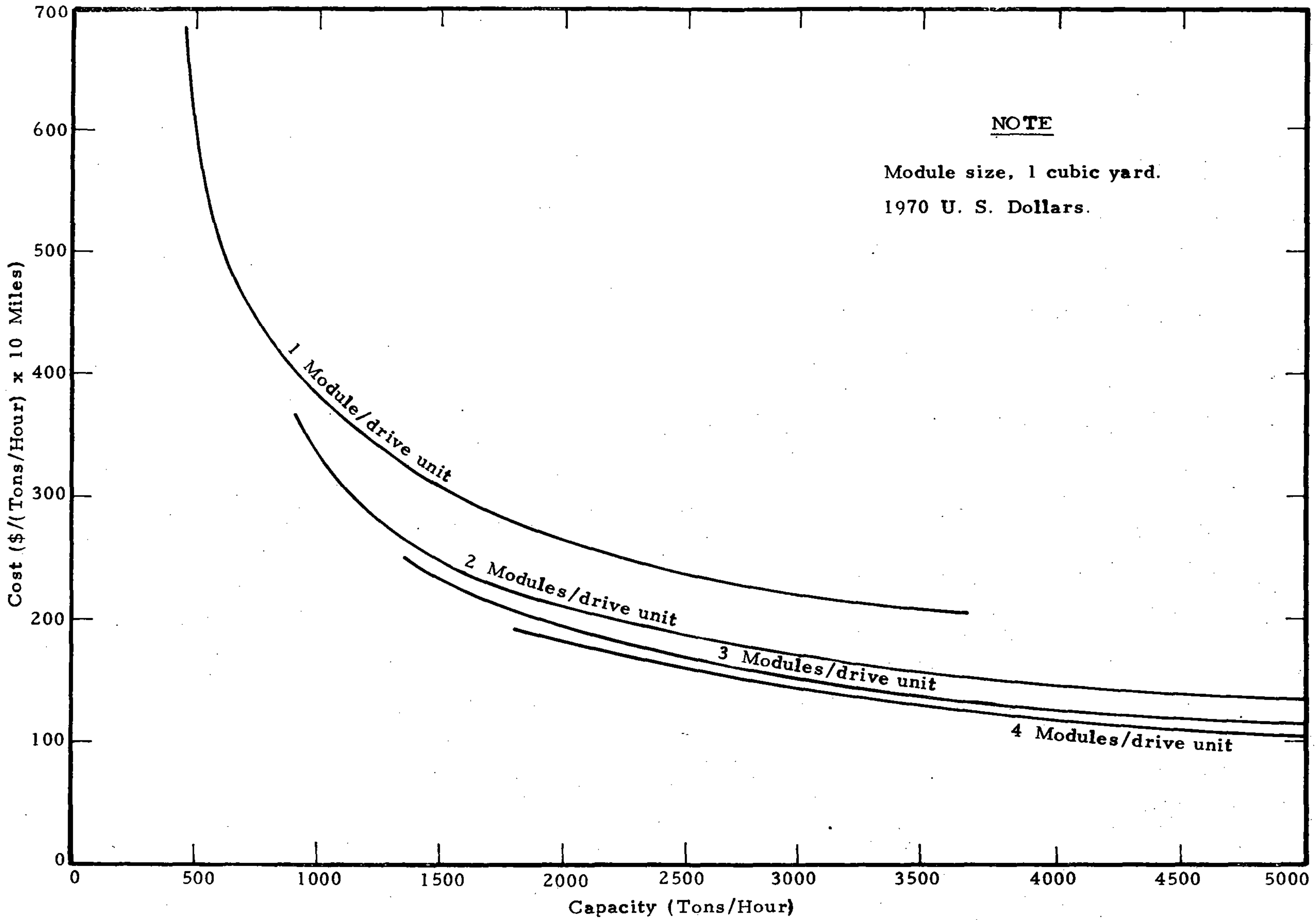

FIGURE 3B-21

SIDERAIL SYSTEM (Horizontal) EQUIPMENT COST

LOCOMOTIVE DRIVE SYSTEM

Performance

The performance model computes cycle time and capacity for combinations of locomotives and cars. Locomotive performance is based on manufacturers' specifications. Car capacity and weight are also based on data collected from manufacturers and handled in parametric form. The total gross weight of the train is computed first for both empty and loaded cases. In equation form,

$$G_1 = NC_1 + W_\ell$$

$$G_2 = NC_2 + W_\ell$$

where

G = gross weight of train, tons
1 empty, 2 loaded

N = number of cars

C = capacity of cars, tons
1 empty, 2 loaded

W_ℓ = weight of locomotive, tons

The weight per axle, a term required to compute train resistance, is computed from the gross weight.

$$W_1 = G_1/(NM + Q_4) \quad \text{(empty)}$$

$$W_2 = G_2/(NM + Q_4) \quad \text{(full)}$$

where

$W_{1,2}$ = average weight per axle
1 empty, 2 loaded

M = number of axles per car

Q_4 = number of axles on locomotive

The locomotive resistance is computed using an approximation of the normal expression for this term.

$$R_1 = G_1 \,(1.2 + 29/W_1 + 0.0005\, AV_1^2/W_1N + 0.045V_1)$$

and

$$R_2 = G_2 \,(1.2 + 29/W_2 + 0.0005\, AV_2^2/W_1N + 0.045V_2)$$

The tractive effort of the locomotive is balanced against the train resistance to compute the balancing velocity or top speed. The tractive effort for a locomotive can be approximated by the expressions

$$TE_1 = R_1 = \frac{0.72\ HP \times 375}{V_1}$$

$$TE_2 = R_2 = \frac{0.72\ HP \times 375}{V_2}$$

where horsepower (HP) is computed as a function of locomotive weight based on the average horsepower recommended for various diesel-powered locomotives ranging in weight from 8 to 100 tons. As a practical consideration, top velocities are limited to 45 miles per hour.

The locomotive acceleration is computed by assuming that the traction available is limited to $0.2 \times W_\ell$, and that acceleration is constant until a top speed is reached or until 45 miles per hour is reached. The distance required to accelerate is calculated by the expressions

$$L_1 = \frac{1}{2}\left(\frac{0.2\ W_\ell}{\frac{G_1 \times 2000}{g} \times \frac{5280}{3600}}\right)(T_1)^2$$

$$L_2 = \frac{1}{2}\left(\frac{0.2\ W_\ell}{\frac{G_2 \times 2000}{g} \times \frac{5280}{3600}}\right)(T_2)^2$$

where

L_1 = distance to accelerate unloaded,

L_2 = distance to accelerate loaded.

The braking distance has been assumed to be equal to the acceleration distance. The cycle time elements are computed as follows:

$$L_{v\ell} = L - 2L_1$$

$$L_{vu} = L - 2L_2$$

where

$L_{v\ell}$ = length of run at top speed, loaded, and

L_{vu} = length of run at top speed, unloaded.

$$T_{v\ell} = \frac{L_{v\ell}}{V_1}$$

$$T_{vu} = \frac{L_{vu}}{V_2}$$

where

$T_{v\ell}$ = time at topspeed, loaded, and

T_{vu} = time at top speed, unloaded.

Also, let

T_ℓ = time to load train,

T_u = time to unload (1 minute), and

T = cycle time

$$T = T_{v\ell} + T_\ell + T_u + T_{vu} + 2T_1 + 2T_2$$

T_ℓ, the time to load is not specified but computed based on the requirement that one train will be in the loading zone at all times. Therefore, the loading time allowed is

$$T_\ell = \frac{T_{v\ell} + T_u + T_{vu} + 2T_1 + 2T_2}{(X - 1)}$$

where X is the number of trains in the system.

The capacity of the system is then computed based on

$$Q = \frac{N\left(C_2 - C_1\right) 3600(X)}{T_{\ell}}$$

Figure 3B-22 presents useful relationships for rail equipment.

Cost

The system cost model computes equipment investment cost and hourly operating cost. Equipment costs are computed in terms of track costs, locomotive costs, and car costs.

Track - Track material costs are estimated based on Figure 3B-23, by the relationship:

$$\$ = 15 \times L \times 5280$$

This value is doubled for four rail systems.

Locomotive - Locomotive costs are estimated based on Figure 3B-24:

$$\$ = (2000 + 5000/W_{\ell})\, W_{\ell} \times 1.13 \times X \text{ (Diesel)}$$

$$\$ = (2381 + 6441/W_{\ell})\, W_{\ell} \times 1.13 \times X \text{ (Electrical)}$$

Car - Car costs are estimated based on Figure 3B-24. Each car type is characterized by its separate cost expression. Car capacity, C_2, is in tons.

$$\$ = (299 + 854/C_2)\, C_2 \times 1.13 \times (X + 1) \times N \text{ (Granby-type side dump)}$$

$$\$ = (663 + 900/C_2)\, C_2 \times 1.13 \text{ (rotary mine car)}$$

$$\$ = (131 + 1397/C_2)\, C_2 \times 1.13 \text{ (Granby-type dump)}$$

$$\$ = (95 + 119/C_2)\, C_2 \times 1.13 \text{ (conventional mine car)}$$

Since the data from Reference 9 was established in 1967, the 1.13 factor is applied to escalate to 1970 costs.

Operational - The operational costs are based on a crew of 1 man per mile for double track at \$6.60 per hour; 2 men per locomotive at \$7.50 per hour; and 0.5 dispatchers per mile at \$6.60 per hour.

$$C_4 = \$/\text{hr} = 2.5L \times 6.60 + 2 \times X \times 7.50$$

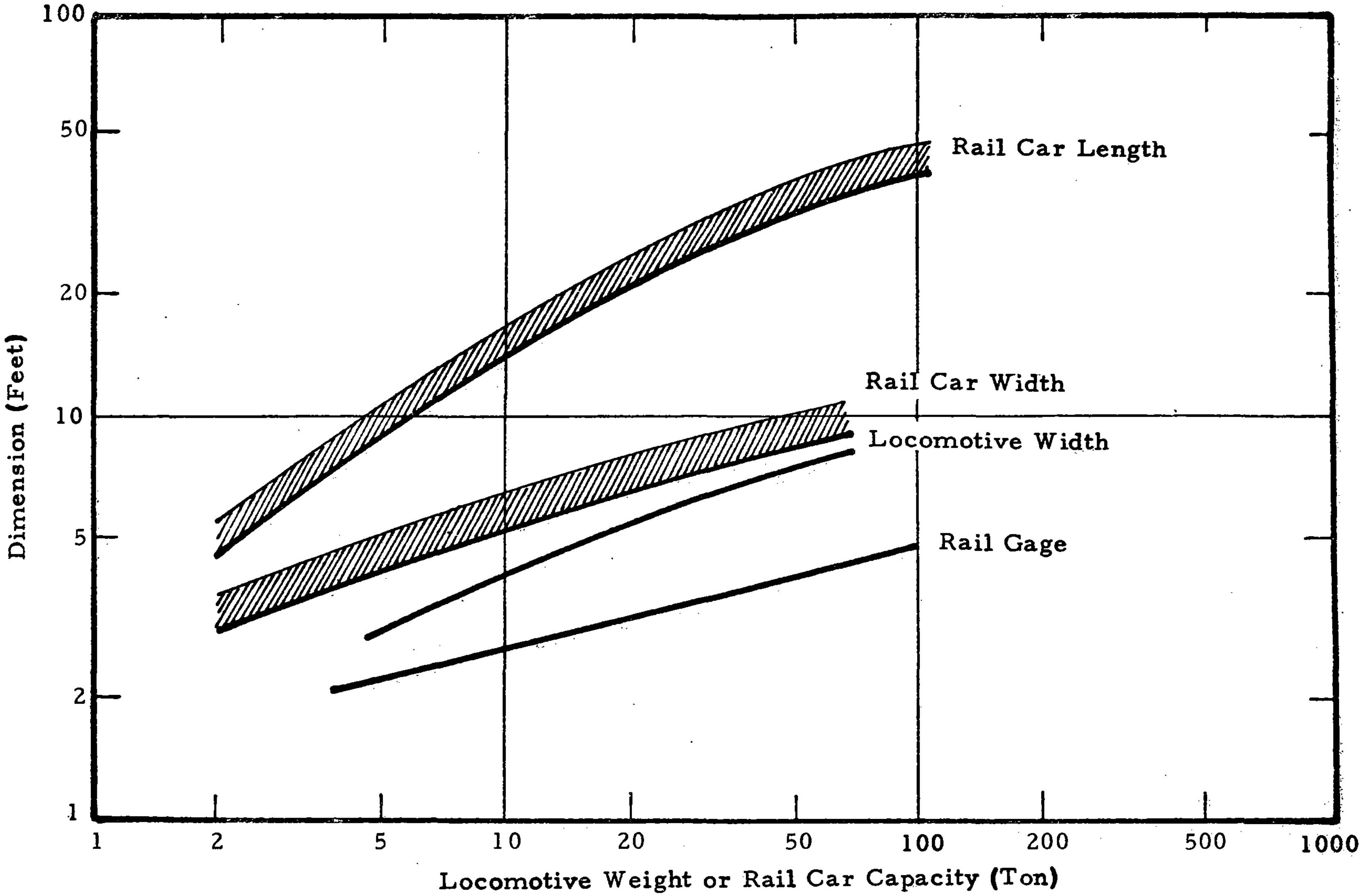

FIGURE 3B-22

CONVENTIONAL RAIL EQUIPMENT DIMENSION/WEIGHT RELATIONSHIPS[9]

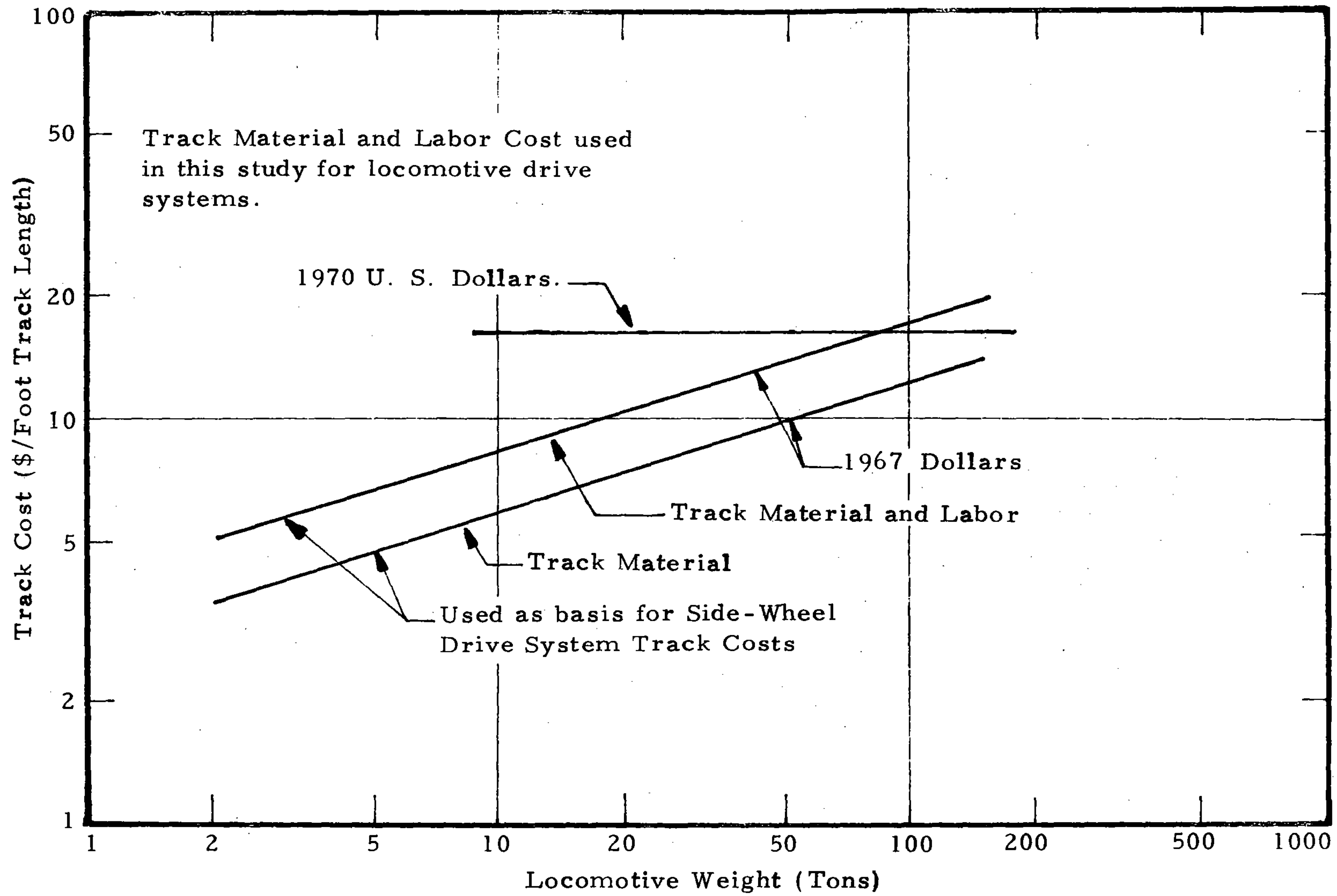

FIGURE 3B-23

CONVENTIONAL RAIL SYSTEMS TRACK COST[9]

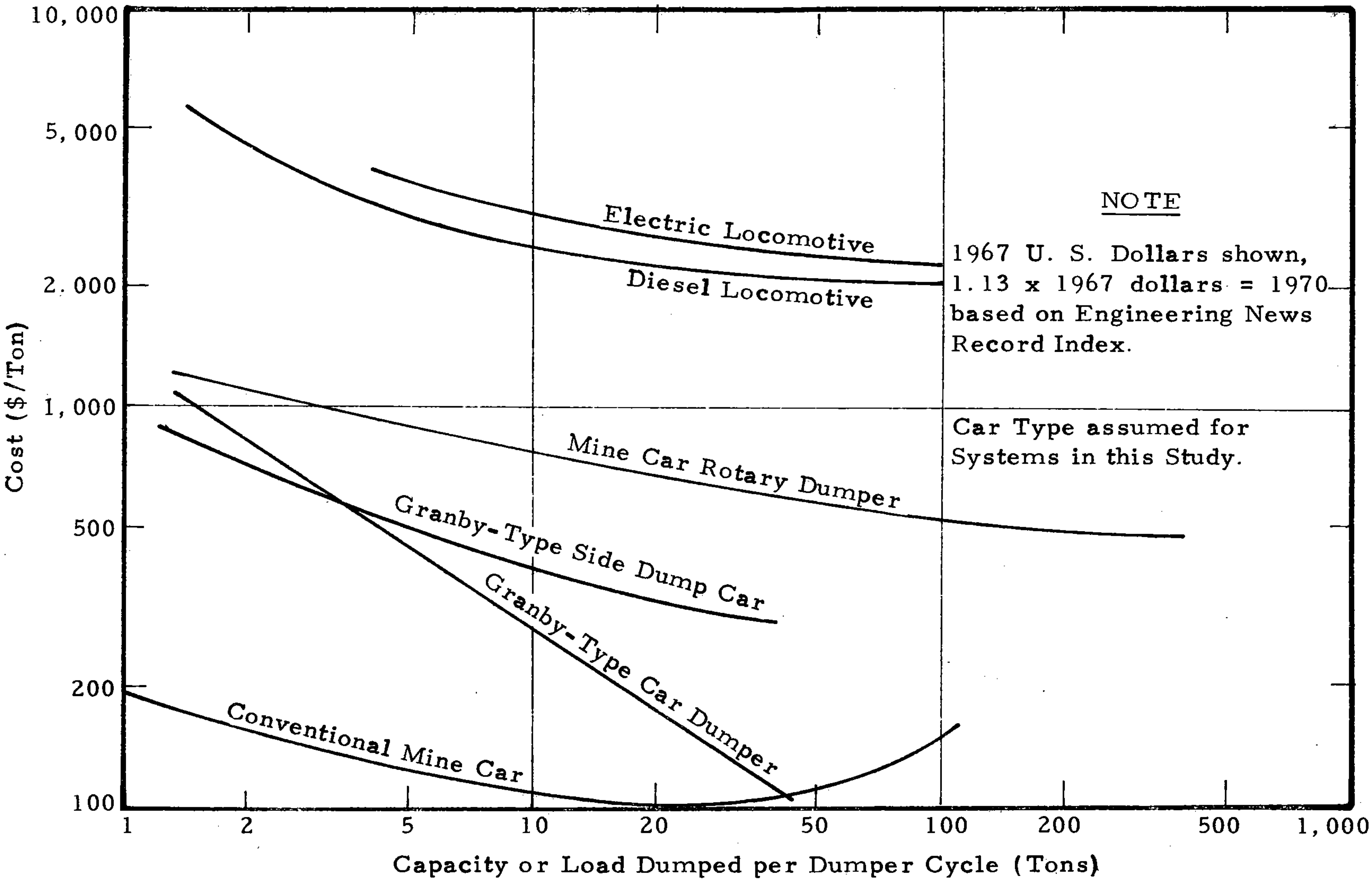

FIGURE 3B-24

LOCOMOTIVE DRIVE SYSTEM EQUIPMENT COST(9)

Fuel (Diesel) - Fuel cost is computed based on tractive effort and the conversion 1 gallon fuel produces 11,500 foot-tons effort.

$$C_5 = \$/hr = \frac{\frac{(60)}{T} \times \left(R_1 + R_2\right) L \times 5,280}{2,000 \times 11,500} \quad (0.14)$$

Reference 6 indicates that locomotive and car maintenance can be computed by applying factors to fuel cost. These relationships are:

Locomotive Maintenance = \$/hr = $C_5 \times 5 \times 0.25$

Car Maintenance = \$/hr = $C_5 \times 5 \times 0.50$

Traffic Control = \$/hr = $C_5 \times 5 \times 0.1$

The total of fuel-related costs is

$$C_6 = \$/hr = C_5 \times 4.25$$

Additional data based on questionnaires returned from a survey of mine railway installations indicates that this is a conservative (high) maintenance estimate. This survey indicates that each railway car requires about 3-man shifts a year, and the ratio between maintenance personnel and locomotives is about 1 man for every 12 locomotives. Either method of estimation contributes costs which are small compared to track maintenance and system operators, so the higher estimate of the two was selected and used.

It should be noted that additional operational and equipment costs can be added as required. The track extension costs have not been included here but are included in the system analysis as a function of advance rates. A surface railroad requires a shop for repair and other general maintenance equipment. For a tunnel railroad, it is estimated that this equipment would cost about 10 percent of the cost of track and rolling stock in a given system.

System Cost/Performance

Figures 3B-25 through 3B-30 present specific operating costs and specific equipment costs for the locomotive drive systems simulated. Three sets of data are presented. Each set represents locomotive and car combinations of a specific size. As a rule of thumb, the locomotive weight is equal to the payload weight of each car. The car weight (tare) is assumed to be 0.5 x payload capacity.

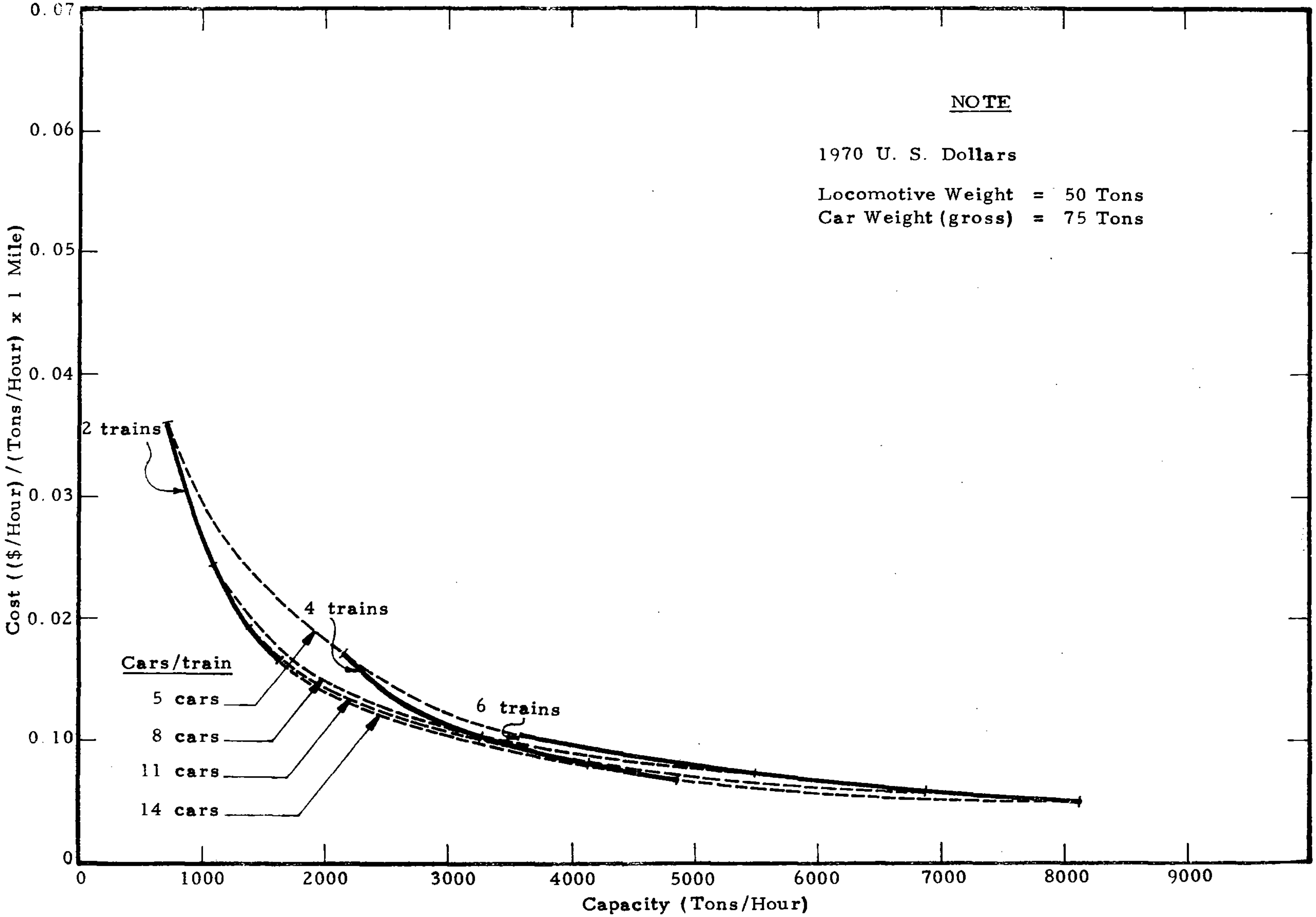

FIGURE 3B-25

LOCOMOTIVE DRIVE SYSTEM OPERATING COST

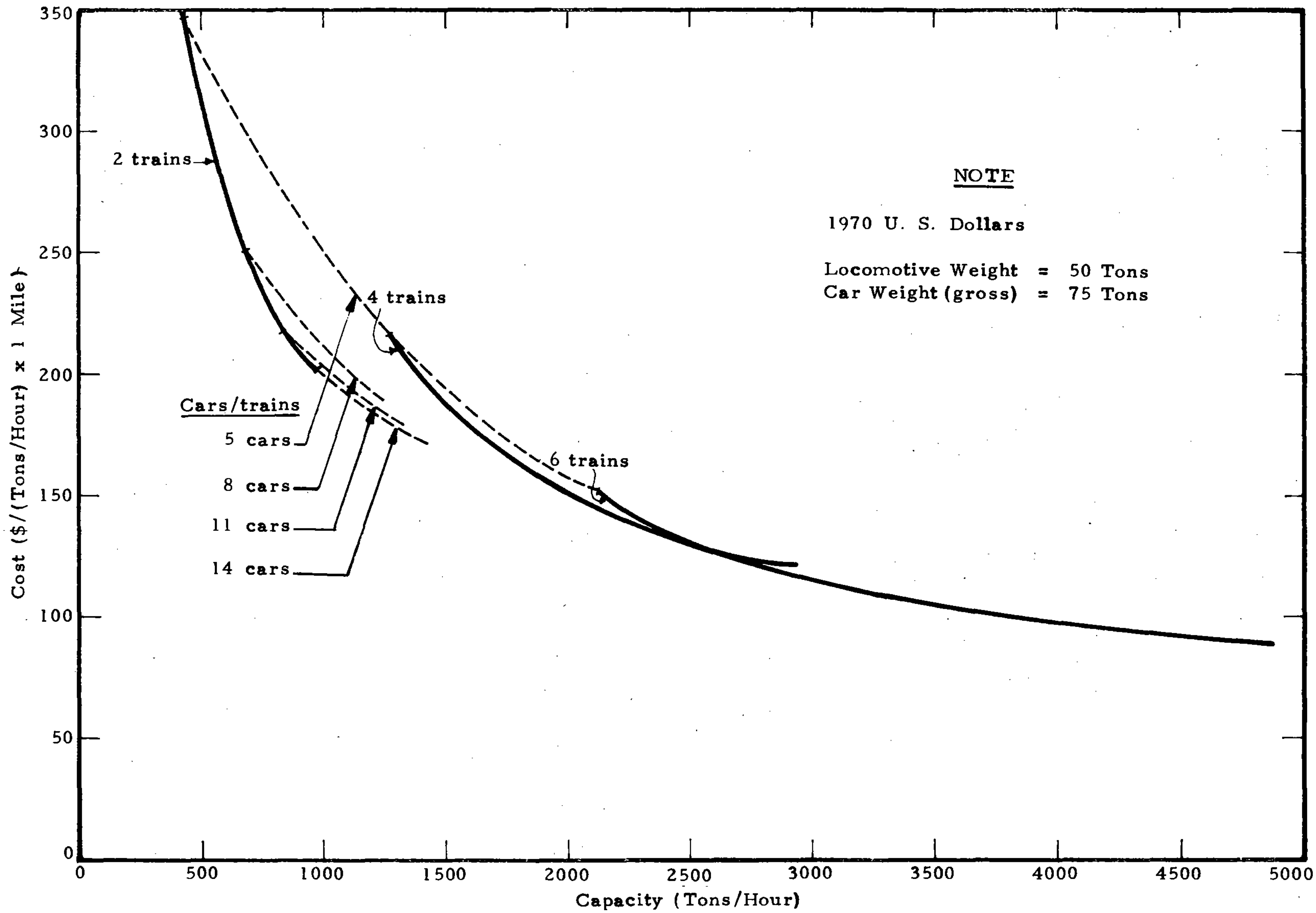

FIGURE 3B-26

LOCOMOTIVE DRIVE SYSTEM EQUIPMENT COST

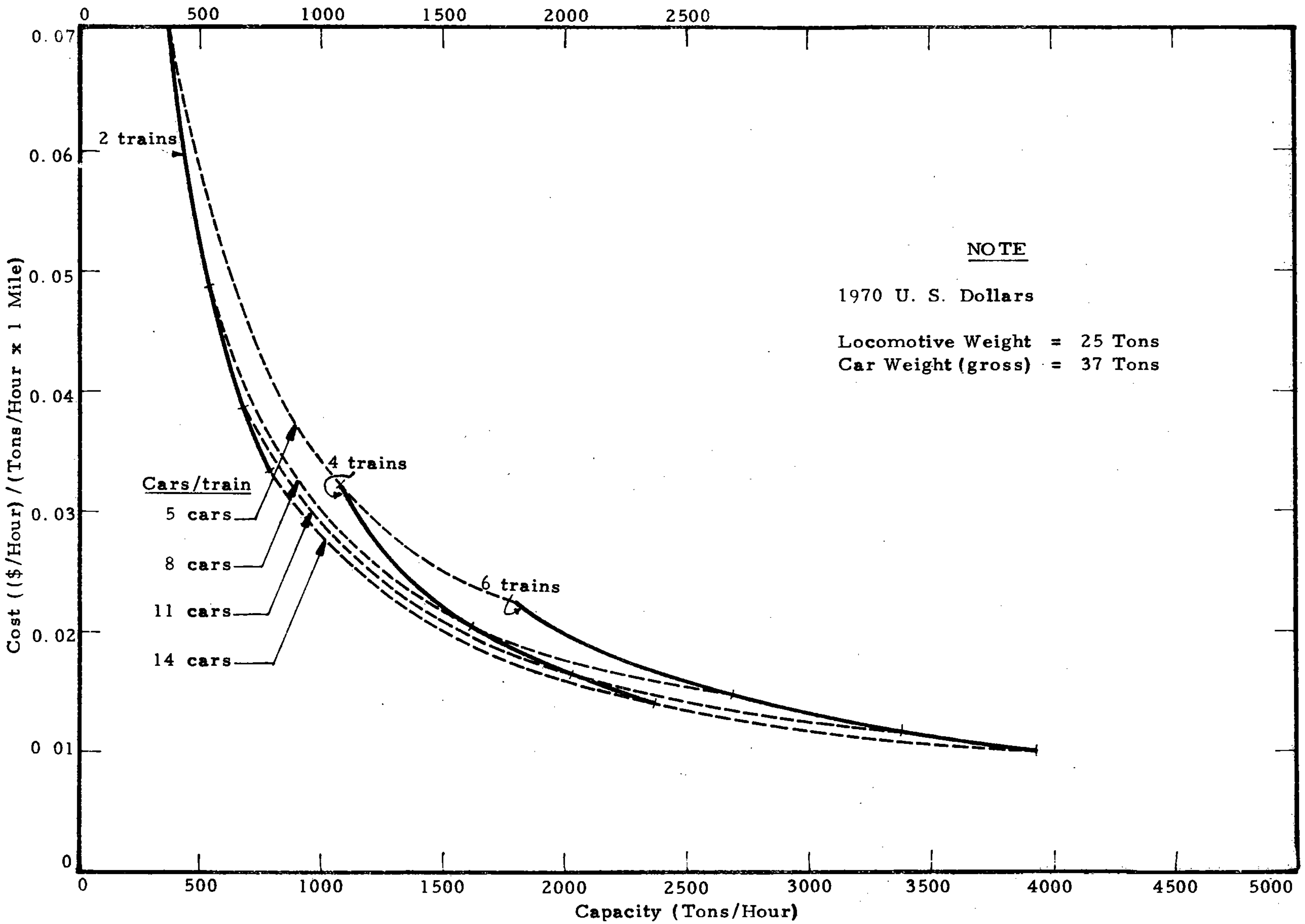

FIGURE 3B-27

LOCOMOTIVE DRIVE SYSTEM OPERATING COST

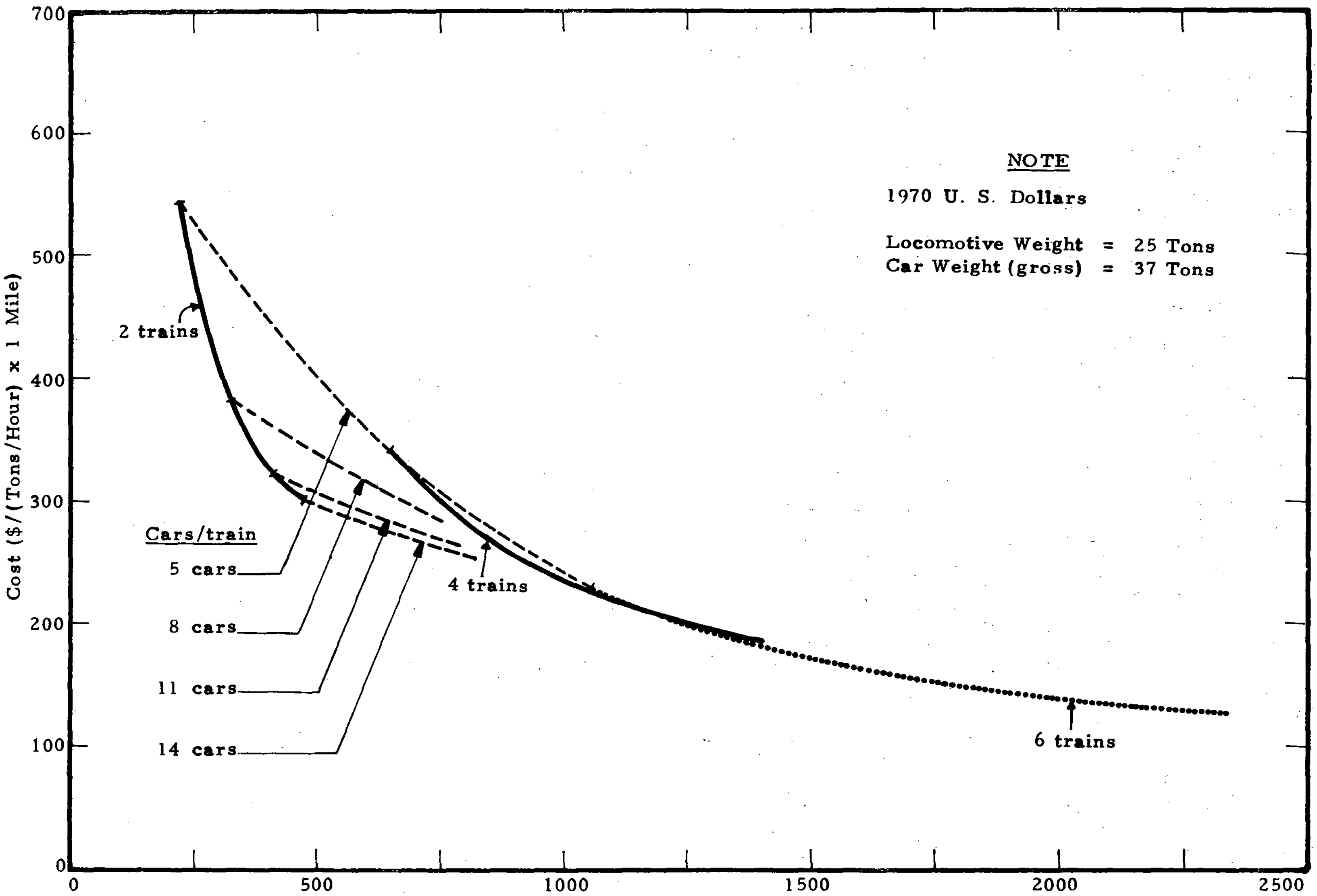

FIGURE 3B-28

LOCOMOTIVE DRIVE SYSTEM EQUIPMENT COST

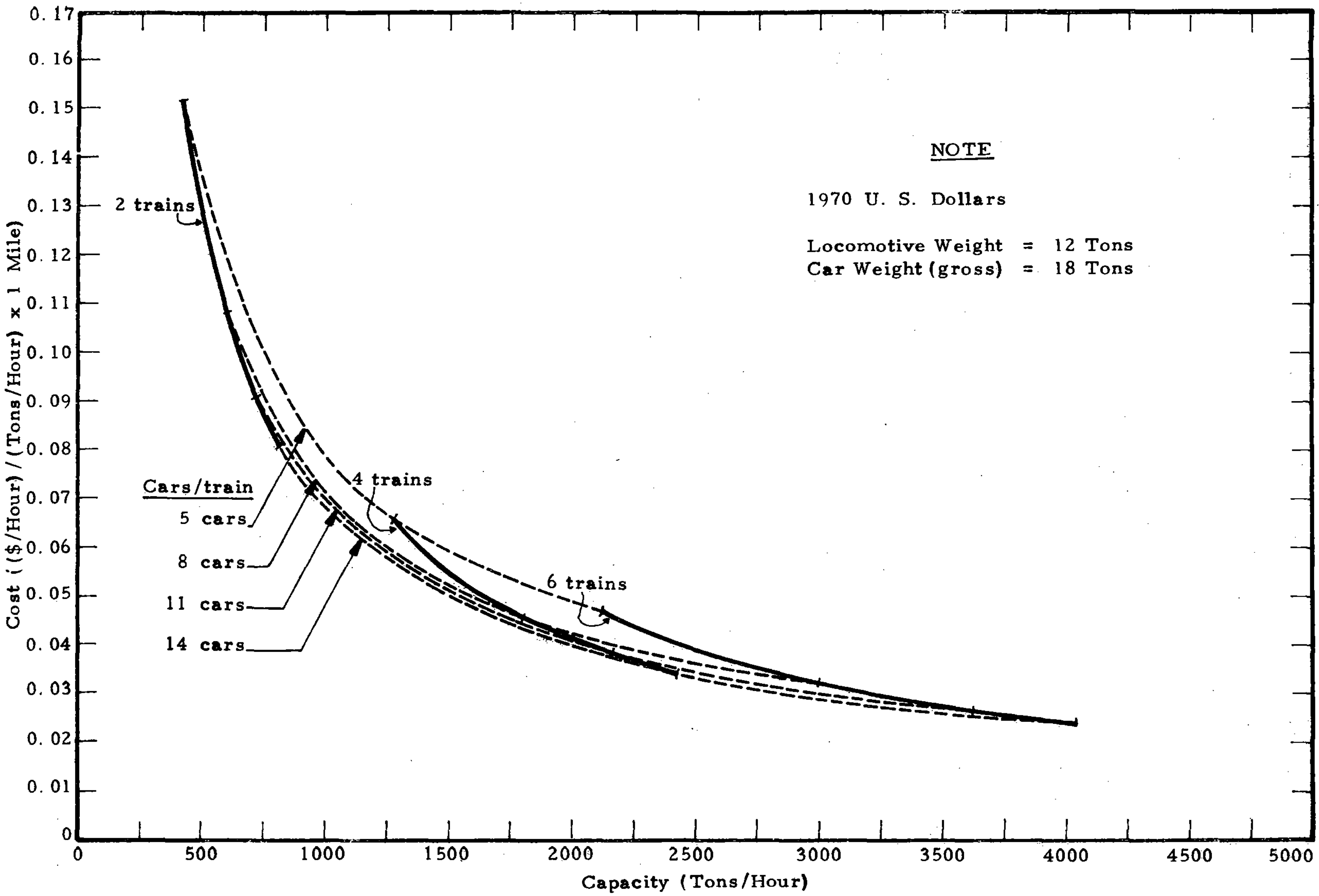

FIGURE 3B-29

LOCOMOTIVE DRIVE SYSTEM OPERATING COST

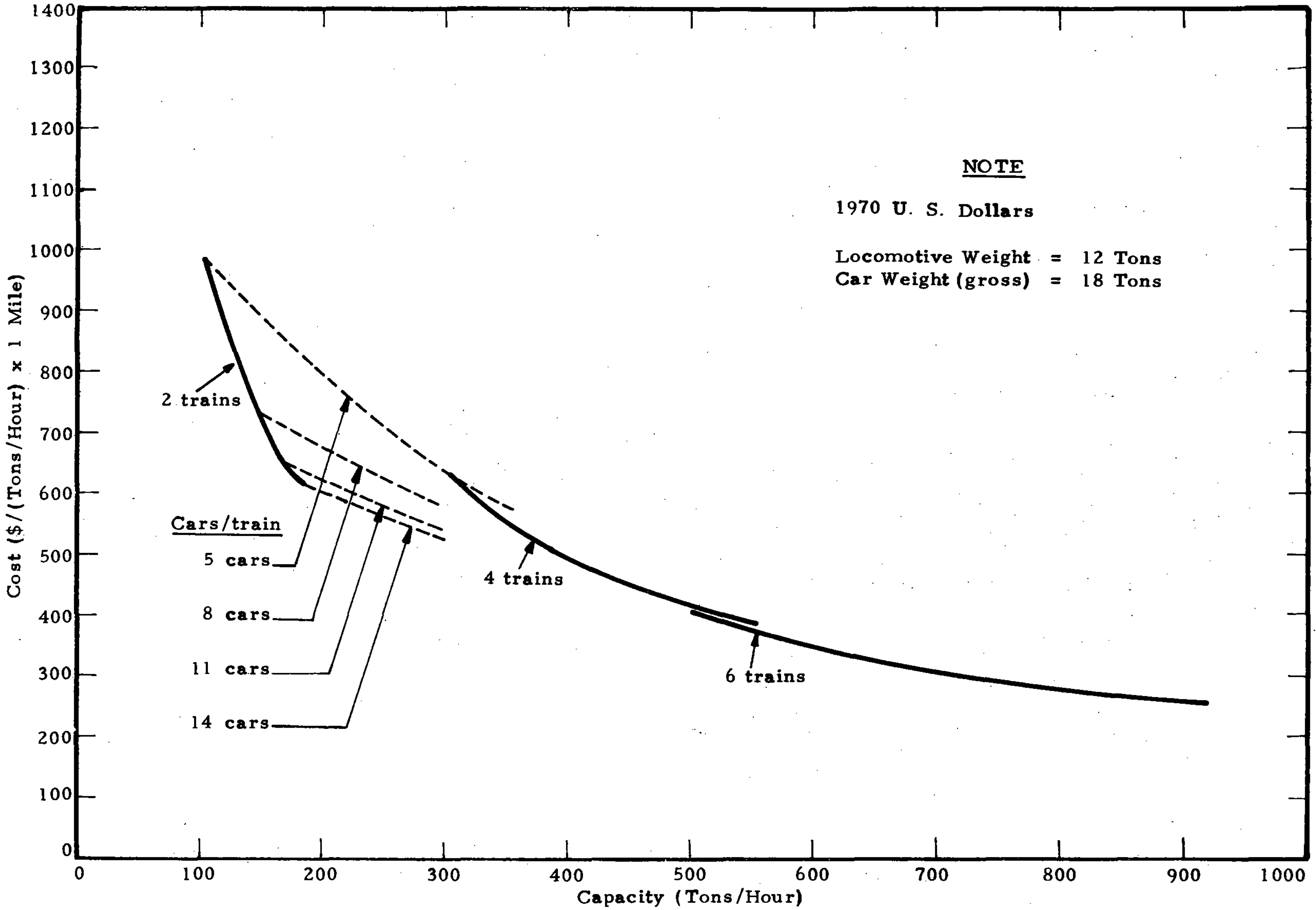

FIGURE 3B-30

LOCOMOTIVE DRIVE SYSTEM EQUIPMENT COST

Cases presented are for

Locomotive Weight	Car Weight (gross)
12 tons	18 tons
25 tons	37 tons
50 tons	75 tons

There is some spread in the specific cost values required to move a given tonnage rate, depending on the train configuration selected within each locomotive/car size category.

HYDRAULIC SYSTEM

Hydraulic System Performance Model

The hydraulic slurry system to transport muck was modeled by a series of steps which generated performance and cost data. The first model is purely performance oriented (Hydrauli System Performance Model); the second model is analogous to the system models developed for other systems (Hydraulic Slurry Cost/Performance Model); and the third model is the integrated system cost model. Each preceding model generates data necessary to support the model which follows as shown in Figure 3B-31.

Figure 3B-32 shows in block diagram form the equations and methods used to compute the basic performance parameters for hydraulic slurry muck removal systems. Return water is assumed to have a very low percentage of solids and behaves according to the well developed fluid flow equations for water. The configuration analyzed is assumed to consist of two vertical segments, one to lift the water transporting solids and one to return water to the system. The configuration also includes two horizontal pipe segments for the same purposes. The performance of each segment is computed separately, but the head loss computations for water are used in the computation of slurry head losses, as described later in this section.

It is emphasized at the outset that the computation of head losses for slurry mixtures is not an exact science, and before design of a slurry transport system, actual tests are run to determine head losses and other factors required to show feasibility and provide design parameters. What is done here is what can be done with published equations and without actual testing. Actual testing is required to optimize critical carrying velocities and establish line size and horsepower requirements which control both investment and operating costs. The empirical relationships used are not always reliable for the system magnitudes covered here. In all cases, a heterogeneous mixture of the first category as defined in Reference 10 was assumed.

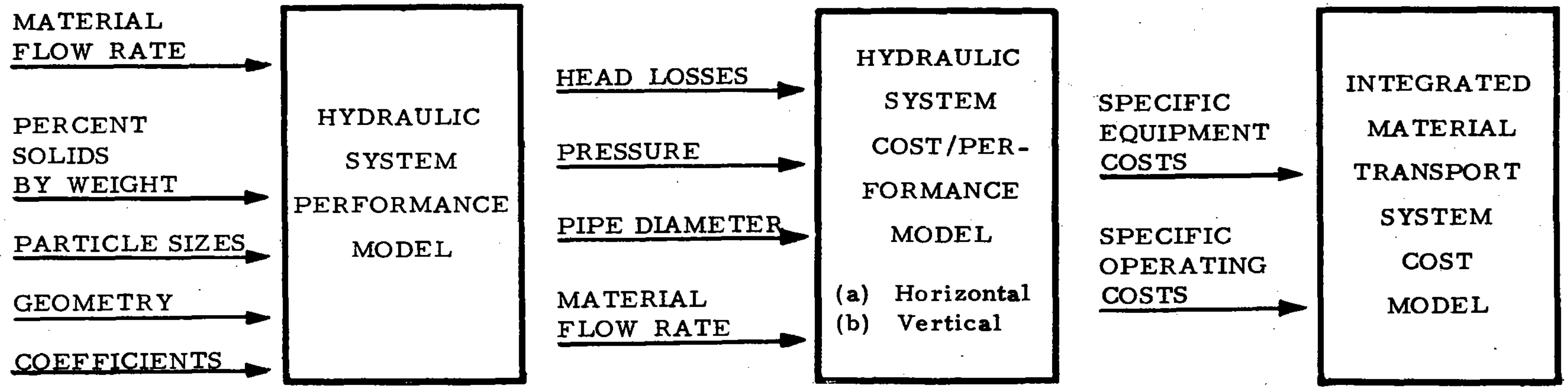

FIGURE 3B-31

HYDRAULIC SYSTEM MODEL

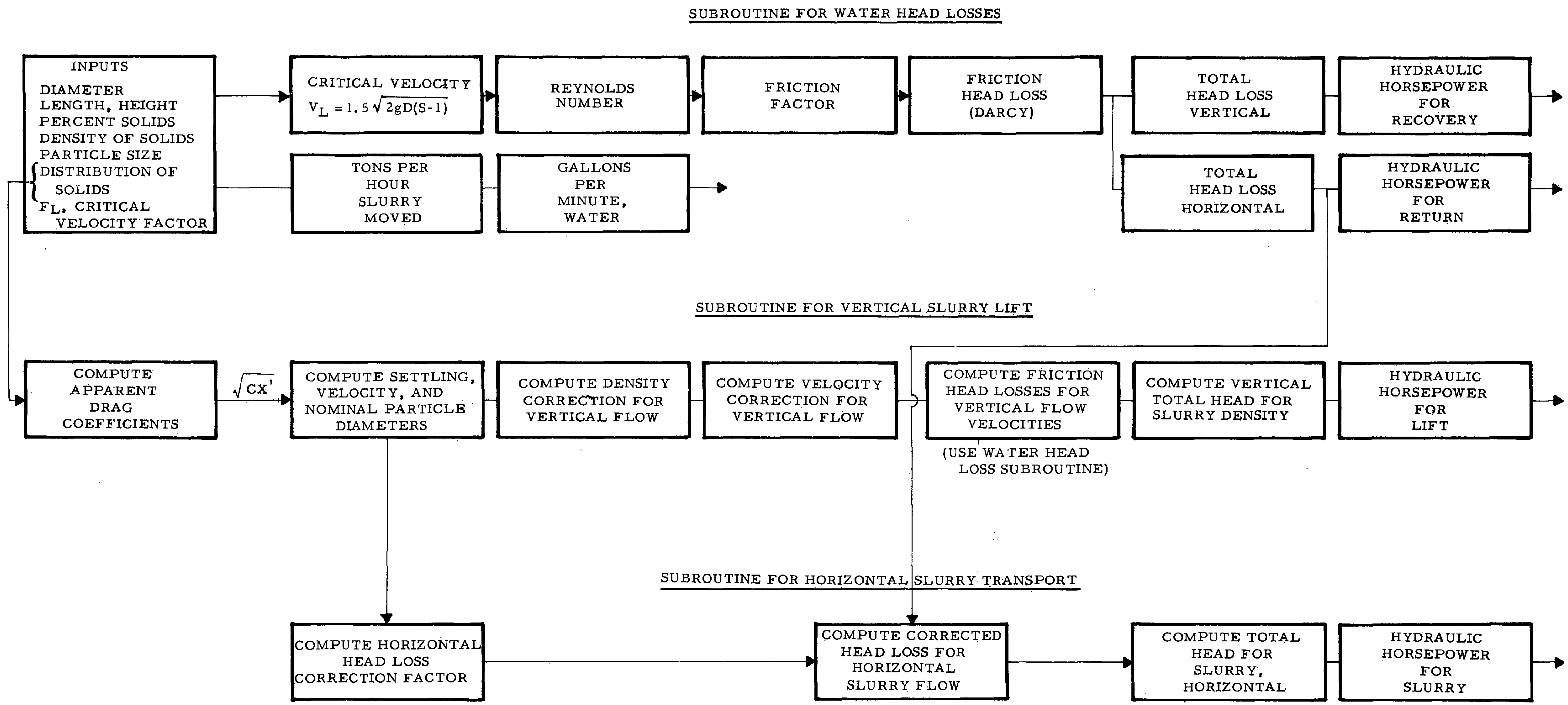

FIGURE 3B-32

HYDRAULIC SYSTEM PERFORMANCE MODEL

Subroutine for Water Head Losses - The equations used are familiar fluid flow equations. Viscosity is computed and using VD/ν, Reynold's number is computed. Using the classical friction factor table, the friction loss equation is

$$H_f = \frac{L V^2}{D \times 2g} \times f$$

where

D = pipe diameter

V = flow velocity

f = friction factor

L = length of pipe

ν = viscosity

The total head is computed by summing the friction head, dynamic head, and head losses due to valves and fittings. For vertical flow the static head is added. The general expression becomes

$$H_t = H_f + H_s + H_v + K_s \frac{V^2}{2g}$$

Apparent Drag Coefficient and Settling Velocity - The apparent drag coefficient was based on data presented in Reference 10. The coefficient $\sqrt{Cx_i'}$ was derived from data based on the particle size and particle size distribution, and the overall coefficient was computed by

$$\sqrt{Cx'} = \sum_{1}^{n} \frac{P_i}{100} \sqrt{Cx_i'}$$

where

P_i is the percentage of particles with apparent drag coefficient $\sqrt{Cx_i'}$

Having determined the drag coefficient, the settling velocity of particles in the mixture is computed by

$$\frac{\sqrt{Cx'}}{\sqrt{0.75 \frac{1}{S - 1} \frac{Cx}{\psi}}} = \sqrt{\frac{gd_n}{W^2}}$$

where

S = the specific gravity of the solid,

Cx' = is determined from Reference 10,

ψ = 0.8, the assumed particle diameter ratio,

d_n = nominal particle diameter (a weighted average),

g = 32.2, and

W = settling velocity.

The settling velocity is used in both vertical and horizontal head loss computations. The percent solids by weight in the mixture is based on horizontal flow, but for vertical flow the density of the mixture changes due to the settling of particles relative to the liquid; i.e., the solids move slower than the liquid flowing upward. Since continuity of both solids and liquids is maintained throughout the pipe, equations were written to relate percent solids by volume in the horizontal pipe with percent solids by volume in the vertical pipe and to further relate the velocities and mixture densities.

Vertical Slurry Flow Calculations - Corrections for the apparent drag coefficient and settling velocity are applied to the equations for water head losses for flow in a vertical pipe to obtain equations for vertical slurry flow. The static and dynamic head is corrected to reflect the appropriate mixture density, and the friction losses reflect the increased fluid velocity relative to horizontal flow.

Horizontal Slurry Flow - The friction head losses for horizontal slurry flow are greater than the corresponding losses for water, but are based on the friction head losses for water corrected by the factor

$$H_{f\ slurry} = H_{f\ water}\ (1 + \phi C_w)$$

where C_w is the percent solids by weight and ϕ is computed by equations developed in Reference 10.

$$\phi = 81 \left[\frac{V^2}{gD\,(s - 1)\cos\alpha} \sqrt{\frac{gd_n}{W}} \sqrt{\frac{s - 1}{1}} \right]^{-3/2}$$

In this equation, α = angle of incline, and the other terms have been previously defined. Any static head changes must be added using the appropriate mixture density.

Performance Data - The basic data obtained from the computer program are presented in Figures 3B-33 through 3B-37. This data group is for material with the following characteristics:

Density	=	2.6
Particle Size	=	50 percent of material is 0.0116 inch or less (used for determination of F_L)
Velocity	=	1.5 critical velocity
Nominal Particle Diameter	=	0.053 feet

Range of Parameters

Pipe Diameters (feet)	Solids by Weight (percent)
1.0	30
1.5	40
2.0	50
2.5	60

The pipe length and vertical height were computed for only one set of conditions since all horsepower and pressure head requirements are basically proportional to the length.

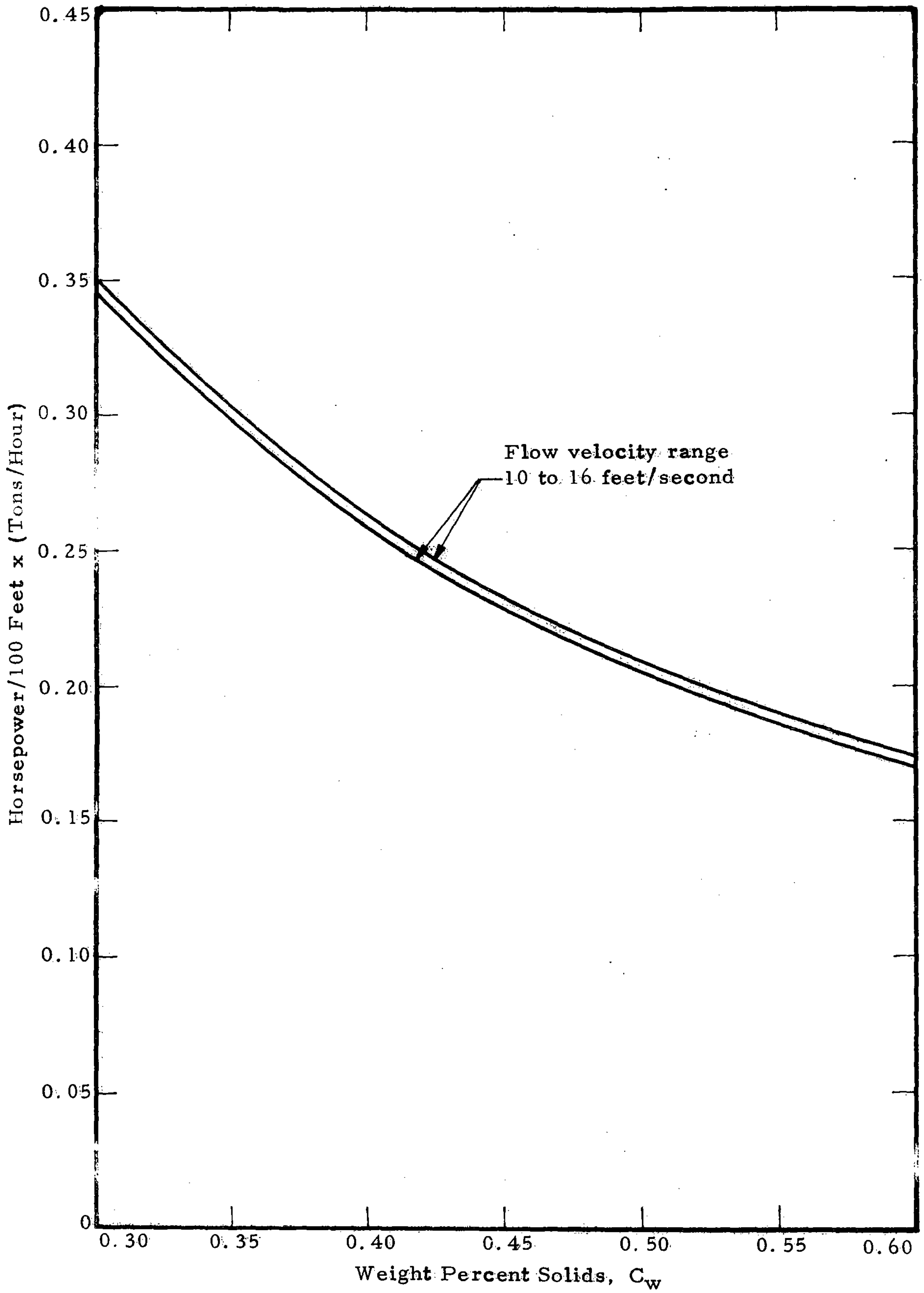

FIGURE 3B-33

HYDRAULIC TRANSPORT (Vertical) POWER REQUIREMENT

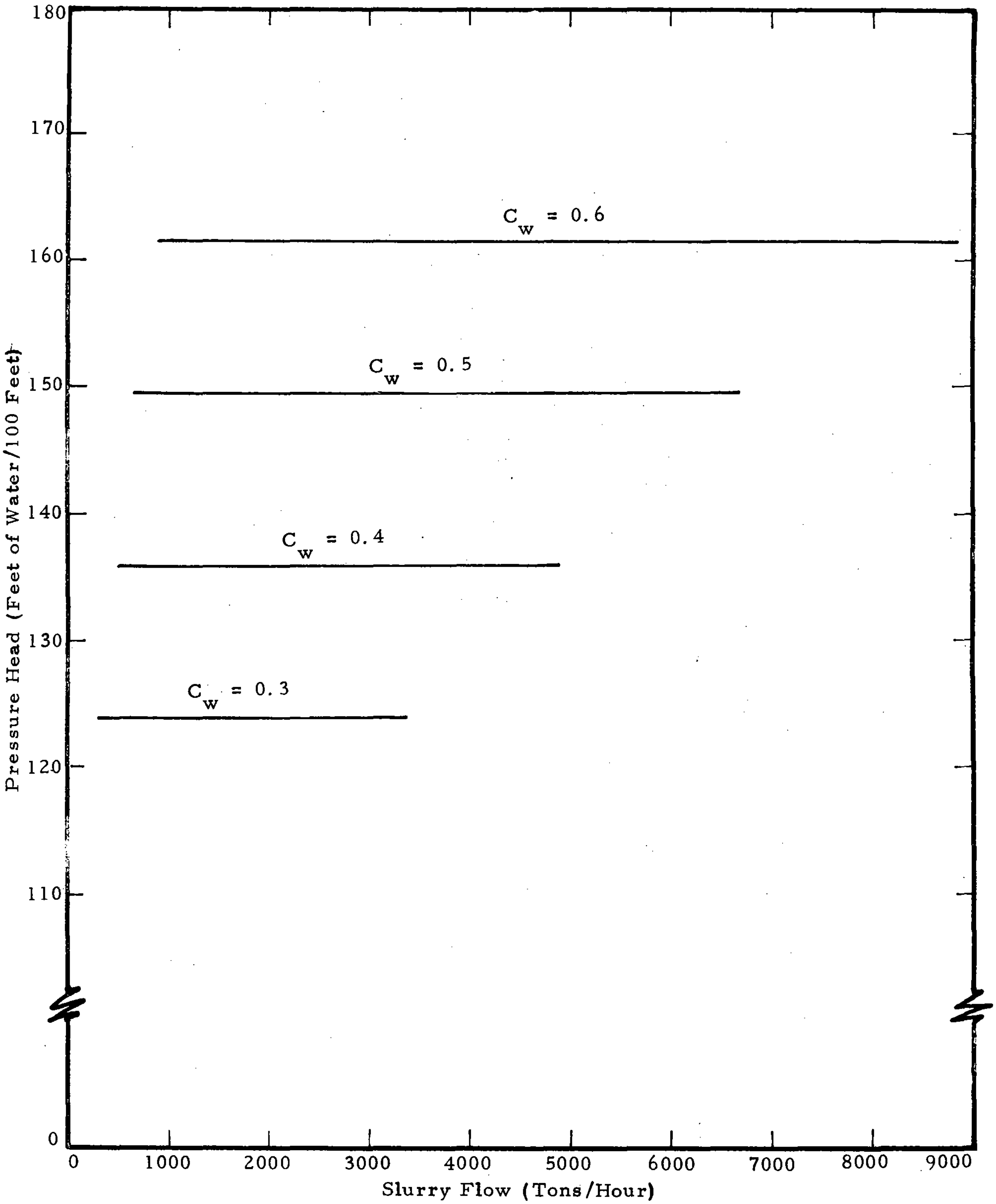

FIGURE 3B-34

HYDRAULIC TRANSPORT (Vertical) PRESSURE REQUIREMENT

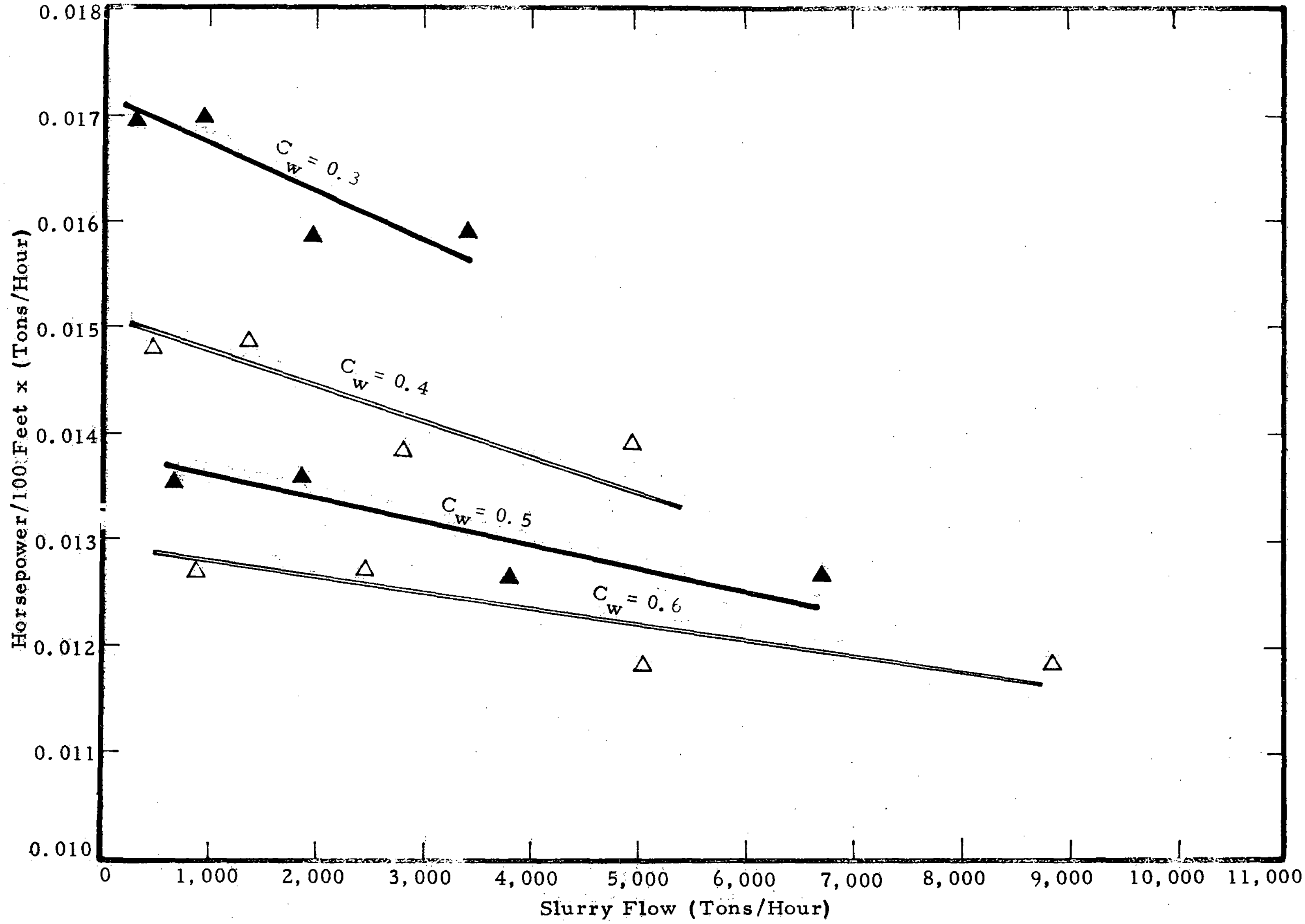

FIGURE 3B-35

HYDRAULIC TRANSPORT (Horizontal) POWER REQUIREMENT

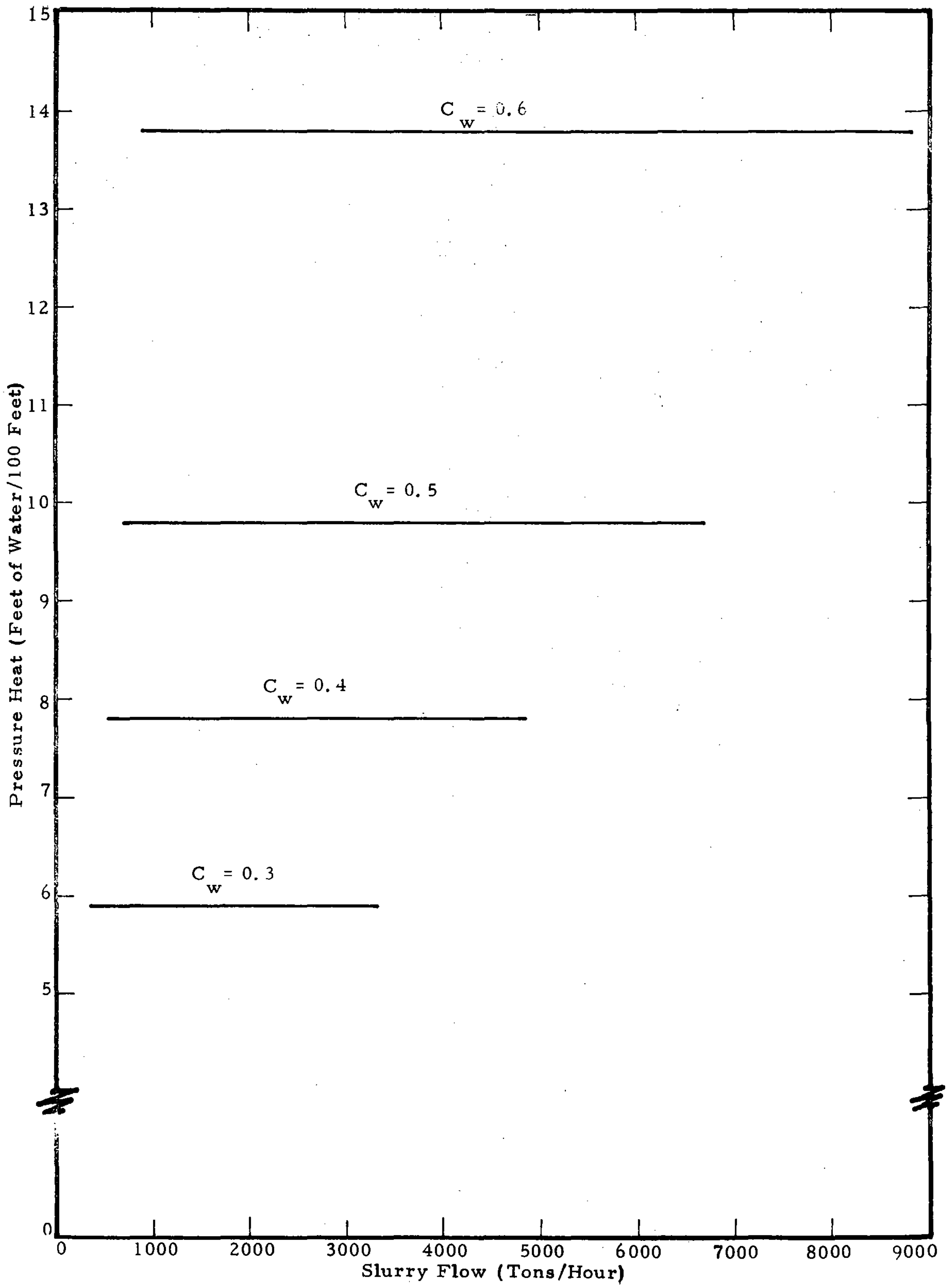

FIGURE 3B-36

HYDRAULIC TRANSPORT (Horizontal) PRESSURE REQUIREMENT

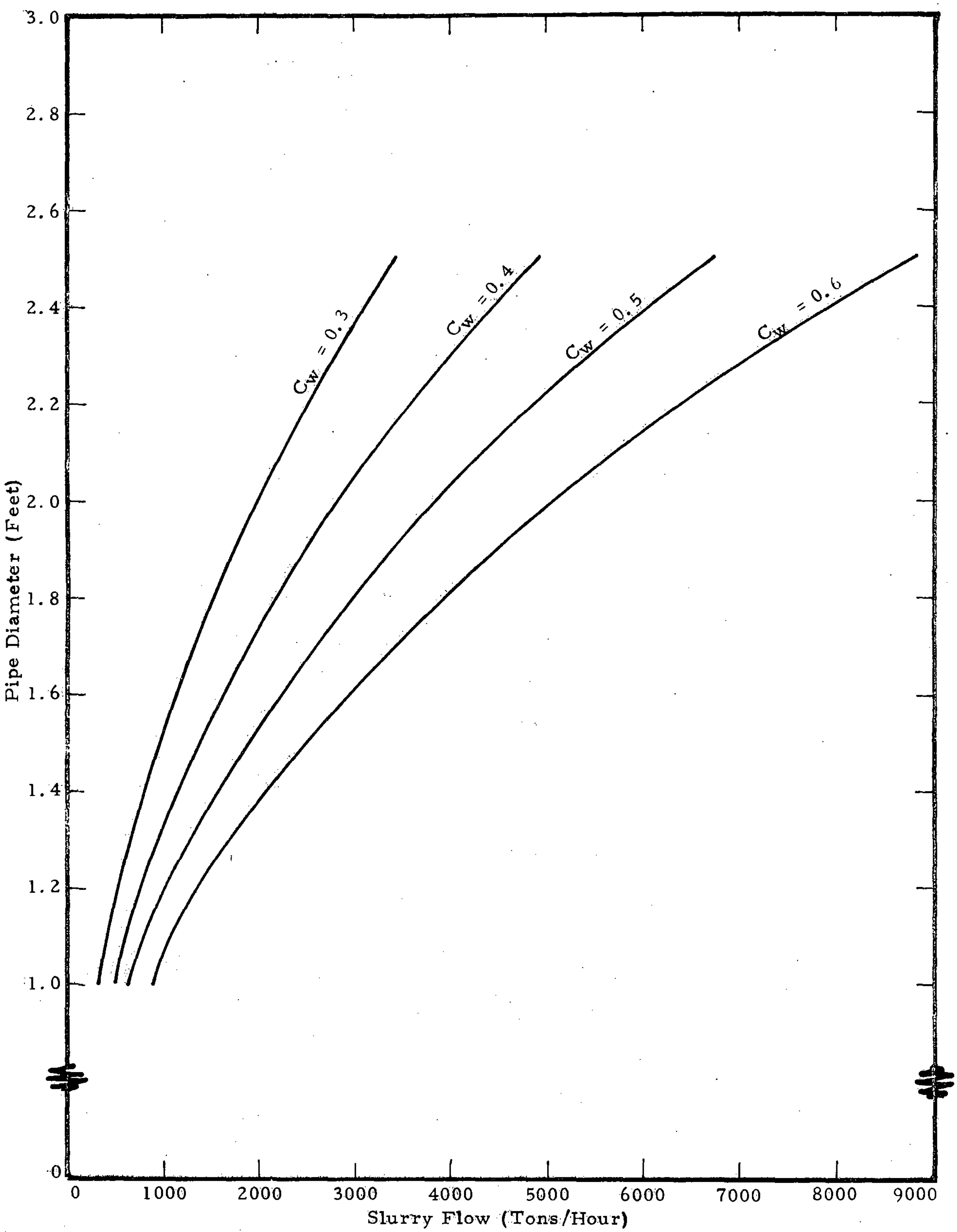

FIGURE 3B-37

HYDRAULIC TRANSPORT PIPE DIAMETER

In the calculations, the return water was assumed to have a high velocity like the slurry mixture. It was later assumed that the slurry pipe and the return water pipe could be of equal diameter, thereby reducing the velocity of the return water to the point where head losses are not too significant, particularly when compared with the large head available from the vertical return water standpipe.

Figure 3B-33 relates the horsepower required to lift slurry vertically for various percent solids, C_W. In the case of vertical flow, the horsepower is not sensitive to pipe diameter or flow velocity, assuming the appropriate values for these terms are selected to match the tonnage lift rate. Figure 3B-34 shows parametric relationships between the total head required per 100 feet of lift height for various material flow rates and various percent solids in the mixture. These two quantities in parametric form are used as inputs to the system cost performance model.

For horizontal flow, Figure 3B-35 presents the specific horsepower required to pump slurry through 100 feet of pipe at the tonnage and percent solids indicated. Similarly, Figure 3B-36 presents data on head losses for horizontal flow given that the tons per hour and percent solids by weight are known. For horizontal transport, the head developed by the centrifugal pumps is assumed to be 200 feet of water each. Knowing the total head computed from data obtained from Figure 3B-36, the number of pumps can be determined; and knowing the total horsepower computed from data from Figure 3B-35, the horsepower per pump can be computed.

For both the horizontal and vertical legs of the system, Figure 3B-37 is applied to determine the appropriate pipe diameter required for selected slurrly flow rates and solid mixture ratios. For horizontal systems, the cost of pipe material can be determined by using Figure 3B-38. For vertical legs, the total head must be used to determine the pipe thickness and weight.

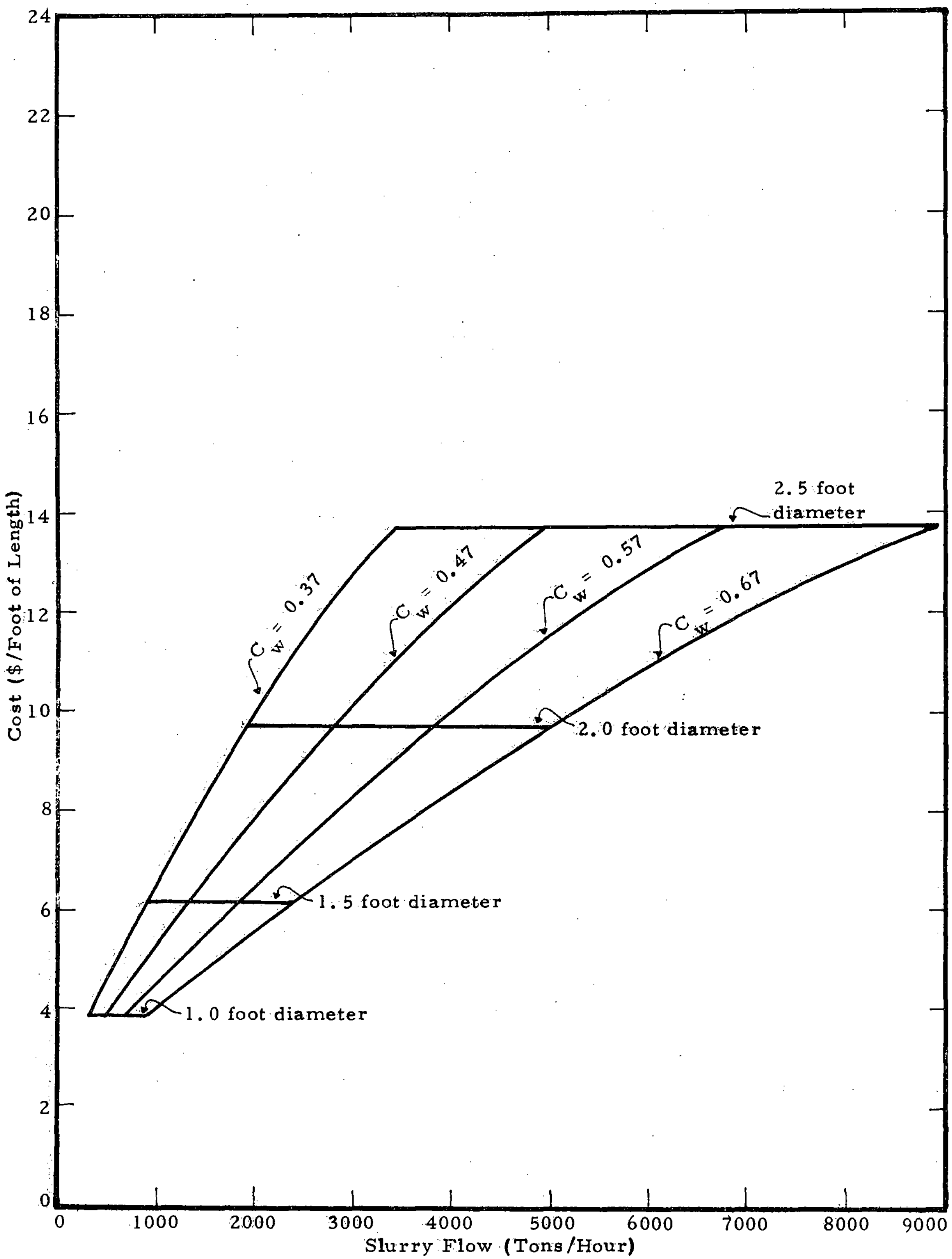

FIGURE 3B-38

HYDRAULIC TRANSPORT (Horizontal) PIPE COST

HYDRAULIC SYSTEM COST/PERFORMANCE MODEL

Since the hydraulic slurry performance model encompassed many variables for which detailed cost sensitivities were not of interest, models were developed which would generate data for input to the integrated system cost model in a manner similar to other system models. In these models, data plotted on Figures 3B-33 through 3B-38 are fit to analytical expressions and are used in parametric form.

Horizontal Transport

Performance - Each system case is specified in terms of tons per hour (T) of solids the system must transport, the percent solids by weight (C_w), and the length of the pipeline (L). The total hydraulic horsepower for slurry is calculated by the expression, derived from Figure 3B-35,

$$HP = \left(0.002 - 0.0128\, C_w - 0.17 \times 10^{-6} T\right) \frac{L}{100}$$

where

L = pipe length in feet

T = tons per hour.

The head for the system is calculated by the expression, derived from Figure 3B-36,

$$H = \left(14.8 + 1{,}953\, C_w - 0.0114T\right) \frac{L}{10{,}000}$$

For horizontal slurry flow, centrifugal pumps are applied. It is anticipated that these pumps would have a head output of about 200 feet each. Hence, the number of pumps is

$$N = \frac{H}{200} .$$

The hydraulic horsepower of each pump can then be computed as

$$H_1 = HP/N = \text{horsepower per pump.}$$

The other term needed to cost the system is the pipe diameter. This is derived from the performance model and presented parametrically on Figure 3B-38 and also by the expression,

$$D \text{ (in feet)} = 2 - 0.211\, C_w + 0.0024T .$$

The performance (in tons per hour) is an input to the system model, and the above parameters (D, N, and H_1) along with other input parameters such as length, percent solids, and pipe segment length, define basic costing relationships.

Cost - The cost of steel pipe required for horizontal slurry transport systems is based on calculations of weight per foot for various diameters, with heads limited to 200 feet and suitable stress safety factors. In addition, 0.125 inch of wall thickness is allowed for wear and 0.0625 inch thickness is allowed for added safety. The established steel cost for the type of pipe used is $0.20 per pound. A simplified expression for pipe cost, derived from Figure 3B-38, is

$$\underset{(\$ \text{ per foot})}{\text{Cost of Pipe Material}} = \underset{(L \text{ and } D \text{ in feet})}{\left(3.16 + D^{1.39}\right) L \times 2}$$

Figure 3B-39 presents a CER for centrifugal pumps including motors and other requirements for an operating unit. The CER for these units is

$$\text{Cost of Pump Units} = N \times H_1 \times 78.43 \times H_1^{-0.0857}$$

Pipe connector costs are based on using Victaulic couplings since this is an easily installed configuration, but the costs for welded joints would be about the same. The CER for couplings is derived from Figure 3B-40.

$$\$/\text{ft} = \frac{1}{L_1}\left(61.54 \times D^{1.69}\right)$$

where L_1 is the length of pipe segment used.

System extension labor costs are included in the integrated model for hydraulic systems.

Energy costs are estimated by the relationship

$$\$/\text{hr} = (\text{HP}/0.56) \times 0.015 \times 0.744 ,$$

assuming a pump efficiency of 0.7 and a motor efficiency of 0.8 .

One maintenance man is required for each group of five slurry pumps and about one man is required every 2 miles to inspect the pipe, plug leaks, and rebuild supports;(11) therefore,

$$\$/\text{hr} = 10\left(\frac{N}{5} + \frac{L}{2}\right) .$$

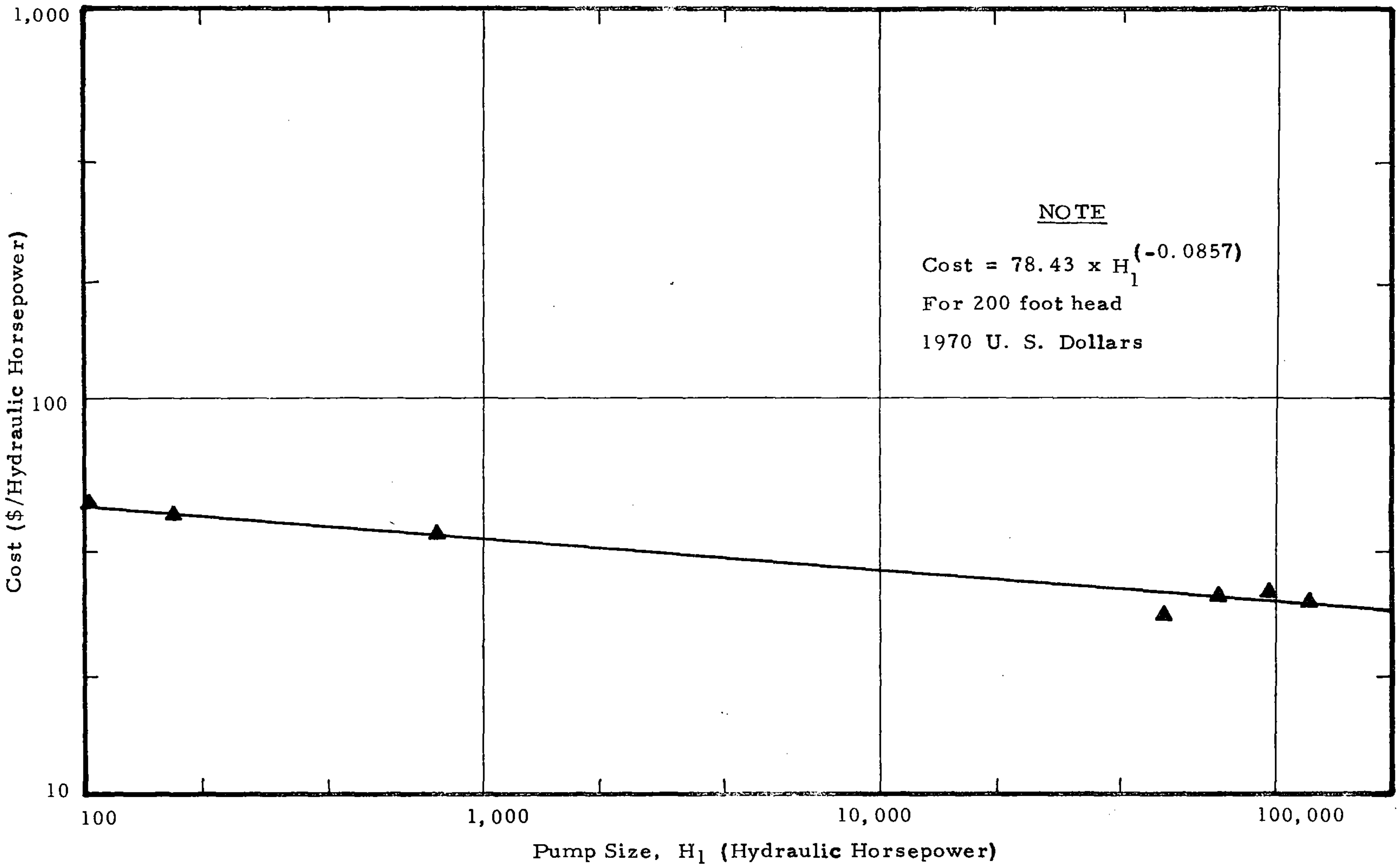

FIGURE 3B-39

CENTRIFUGAL PUMPING SYSTEM EQUIPMENT COST

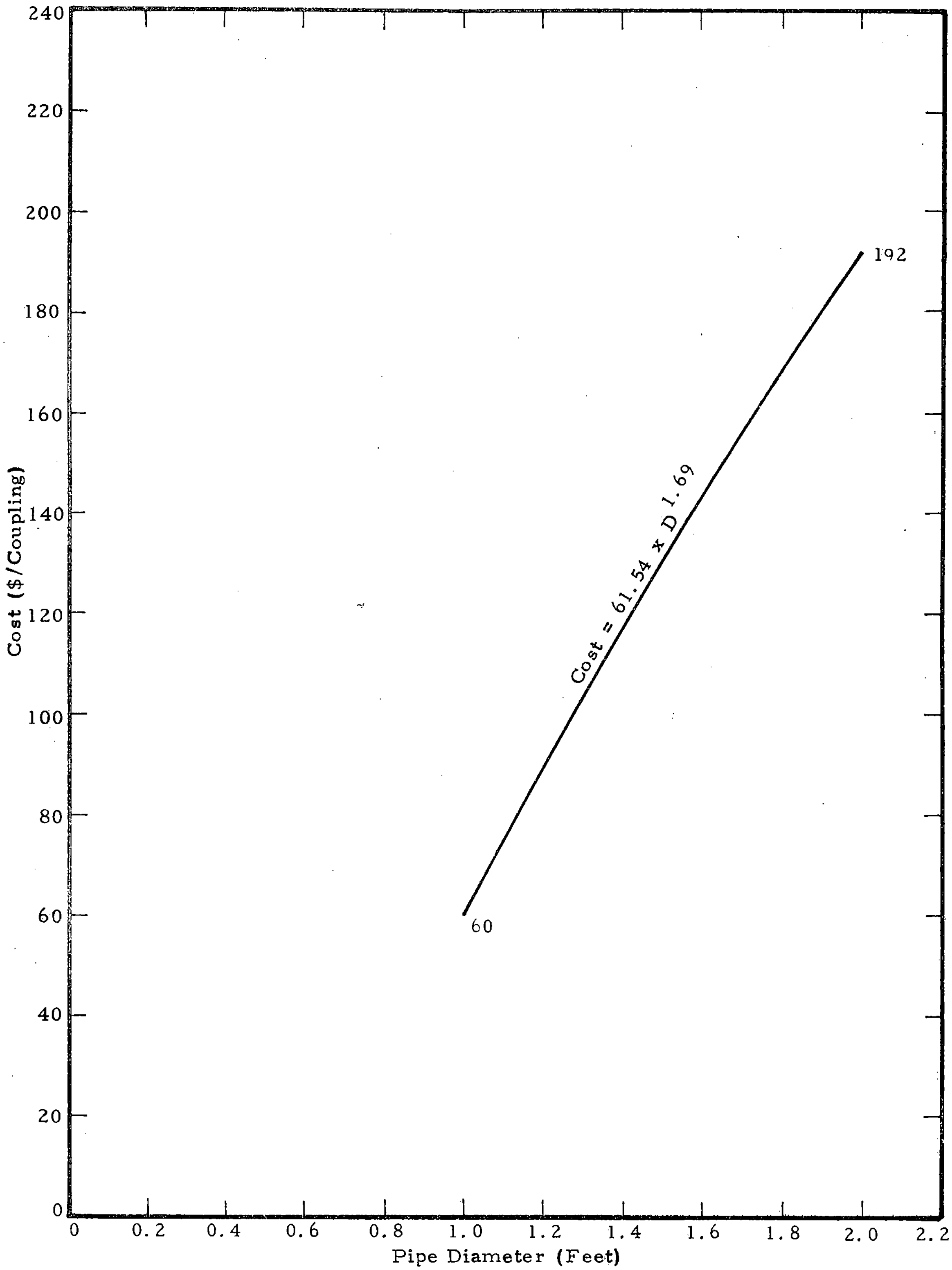

FIGURE 3B-40

PIPE COUPLINGS, EQUIPMENT COST

System Cost/Performance - Operating and equipment costs are summed and ratioed with the capacity and length of the system similar to calculations performed to obtain other system model results. Figures 3B-41 and 3B-42 present these results.

Figure 3B-41 presents specific operating costs for the horizontal transport system. Energy costs are shown separately on this figure but are also included in the total operating costs. Figure 3B-42 shows specific equipment costs as a function of system capacity and percent solids by weight, C_w.

Vertical Transport

Performance - The vertical lift segment for hydraulic slurry operations is based on an extension of the program for horizontal slurry transport. However, an entirely new set of cost and performance expressions must be developed to describe performance and cost.

The head for the vertical system is highly dependent on the depth of the shaft. Using the performance data from Figure 3B-34, the expression for the head required for vertical lift is

$$H = (465 + 566C_w + 0.00147T) \frac{L}{500}$$

where L is the length of the vertical pipe.

Similarly, the horsepower is related by the expression (derived from Figure 3B-33)

$$HP = T\left(0.1133C_w^{0.911}\right) L/100$$

For vertical slurry lift, the use of reciprocating pumps is anticipated. Although several reciprocating pumps might be used (in parallel for capacity), the number of pumps is not too significant from a cost standpoint as will be explained later. The pipe diameter is established in the same manner as for horizontal flow. With these parameters, the vertical lift system can be costed.

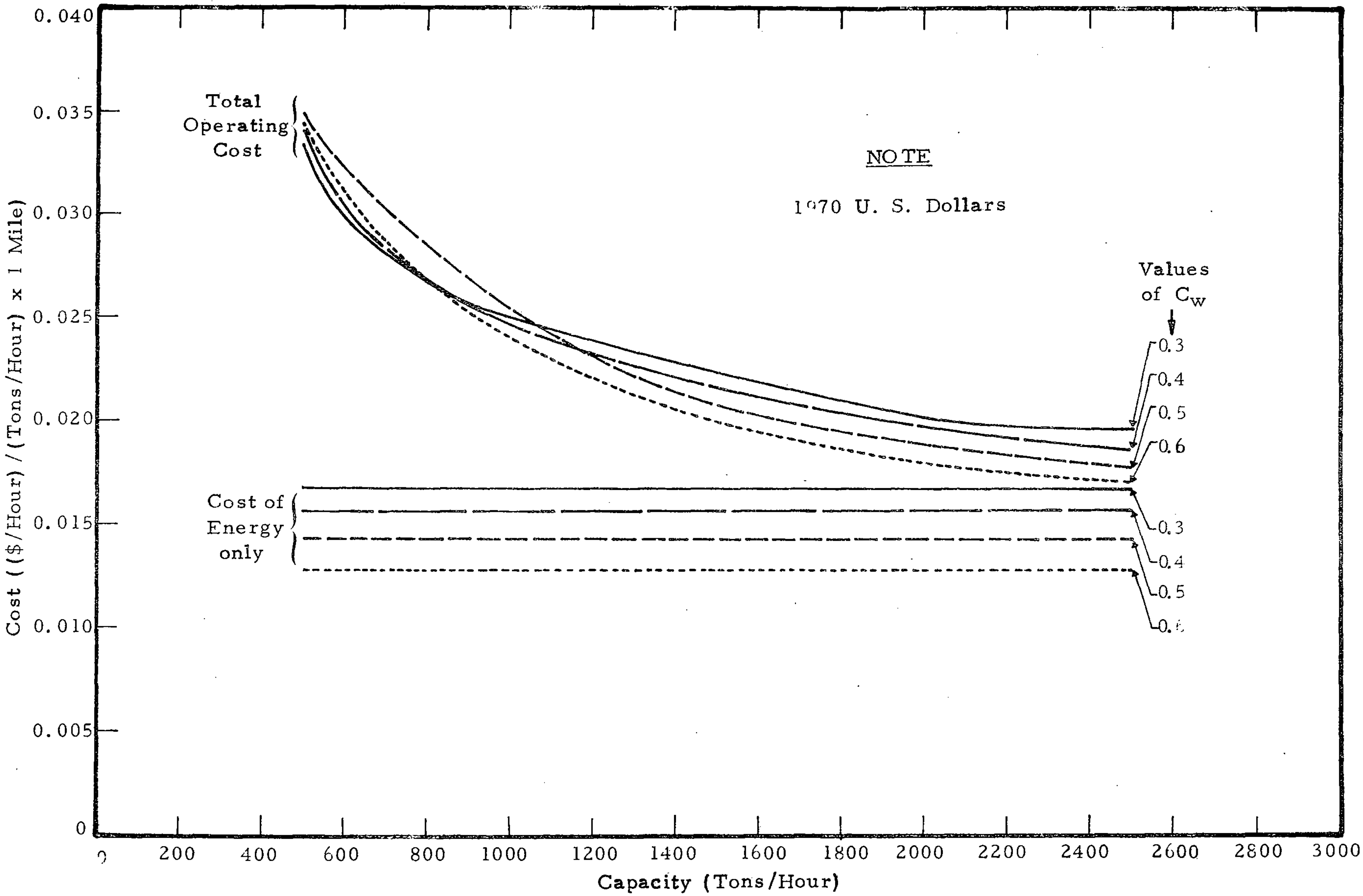

FIGURE 3B-41

HYDRAULIC TRANSPORT (Horizontal) OPERATING COST

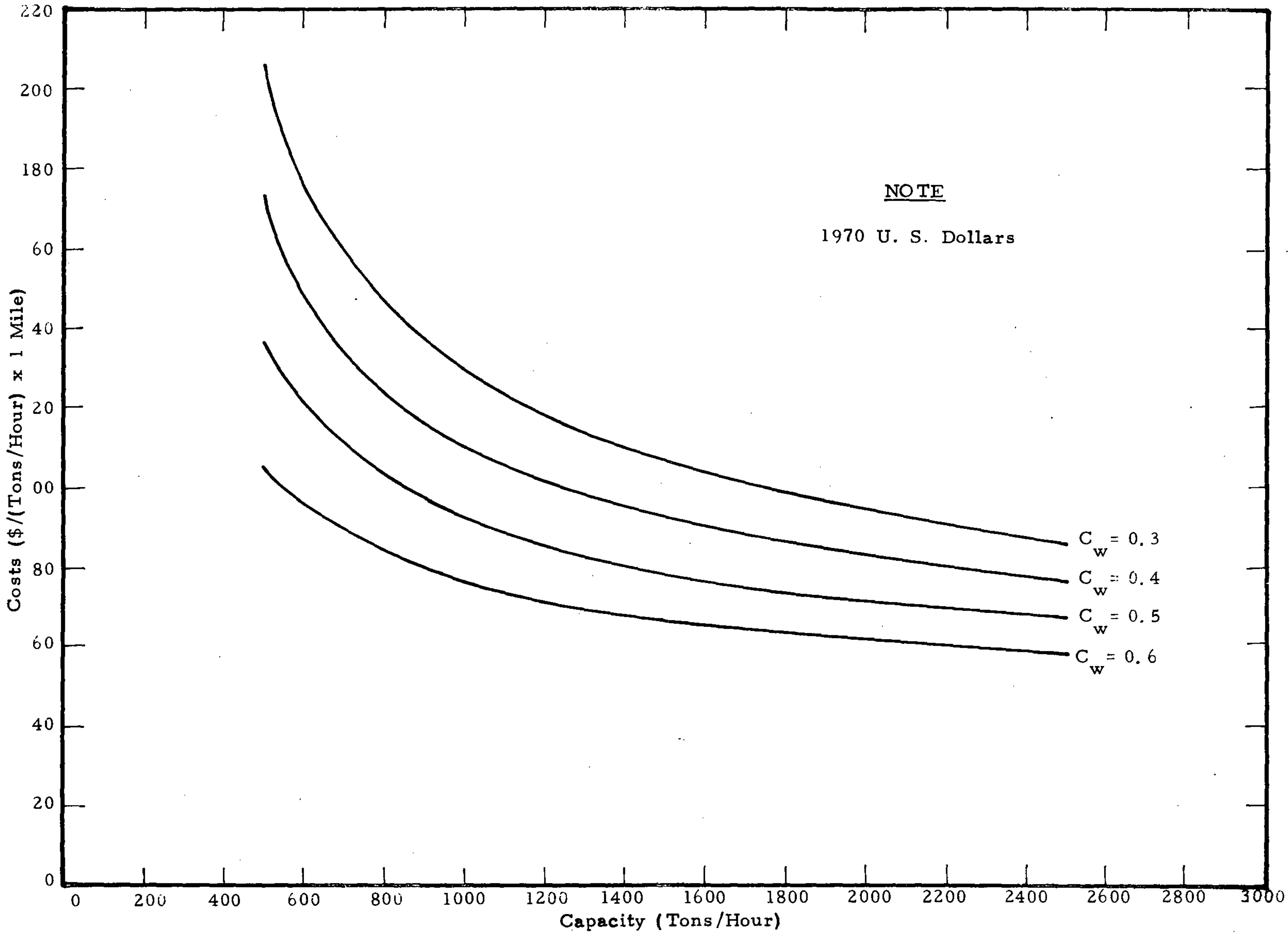

FIGURE 3B-42

HYDRAULIC TRANSPORT (Horizontal) EQUIPMENT COST

Cost - The pipe material costs are expressed by

$$\$/ft = [D \times H(0.15 \times 10^{-3}) + 1.25 + 0.0625] \times D \times 14.2 \ .$$

For large reciprocating pumps, there is an apparent inverse economy of scale. A reciprocating pump rated at 1,440 hydraulic horsepower costs about $97 per horsepower. Another pump rated at 550 hydraulic horsepower costs about $92 per horsepower. An average value of $95 per horsepower was selected as the cost of installed pumping stations in the size and quantity required for a large series of tunnels. Therefore,

$$\$ = HP \times 95$$

Pump costs are based on data from Wilson-Snyder Pump Manufacturers.

A degree of economy can be attained by recovering the energy of the return water; several methods to accomplish this are discussed in Chapter 3. The method assumed in this model uses another reciprocating pump operating as a motor and connected mechanically or hydraulically to the lifting pump. Since this arrangement would add complexity, it was assumed that the recovery and reapplication of about 64 percent of the return energy would cost an additional $95 per installed horsepower for equipment.

The pipeline would be fabricated at the top of the shaft by welding segments and lowering the welded segments as a unit using drill casing techniques. Reference 12 presents weld costs for large diameter casings. These data were projected down to the diameters of interest, and an average wall thickness anticipated for this application was cross-plotted on the casing data as shown on Figure 3B-43. The CER which results is

$$\$ \text{ for welding} = D \times 333 \times \frac{D_1}{L_1}$$

where

D = diameter, feet

L_1 = segment length, feet

D_1 = depth of shaft, feet

Other installation costs are included as elements in the system cost model.

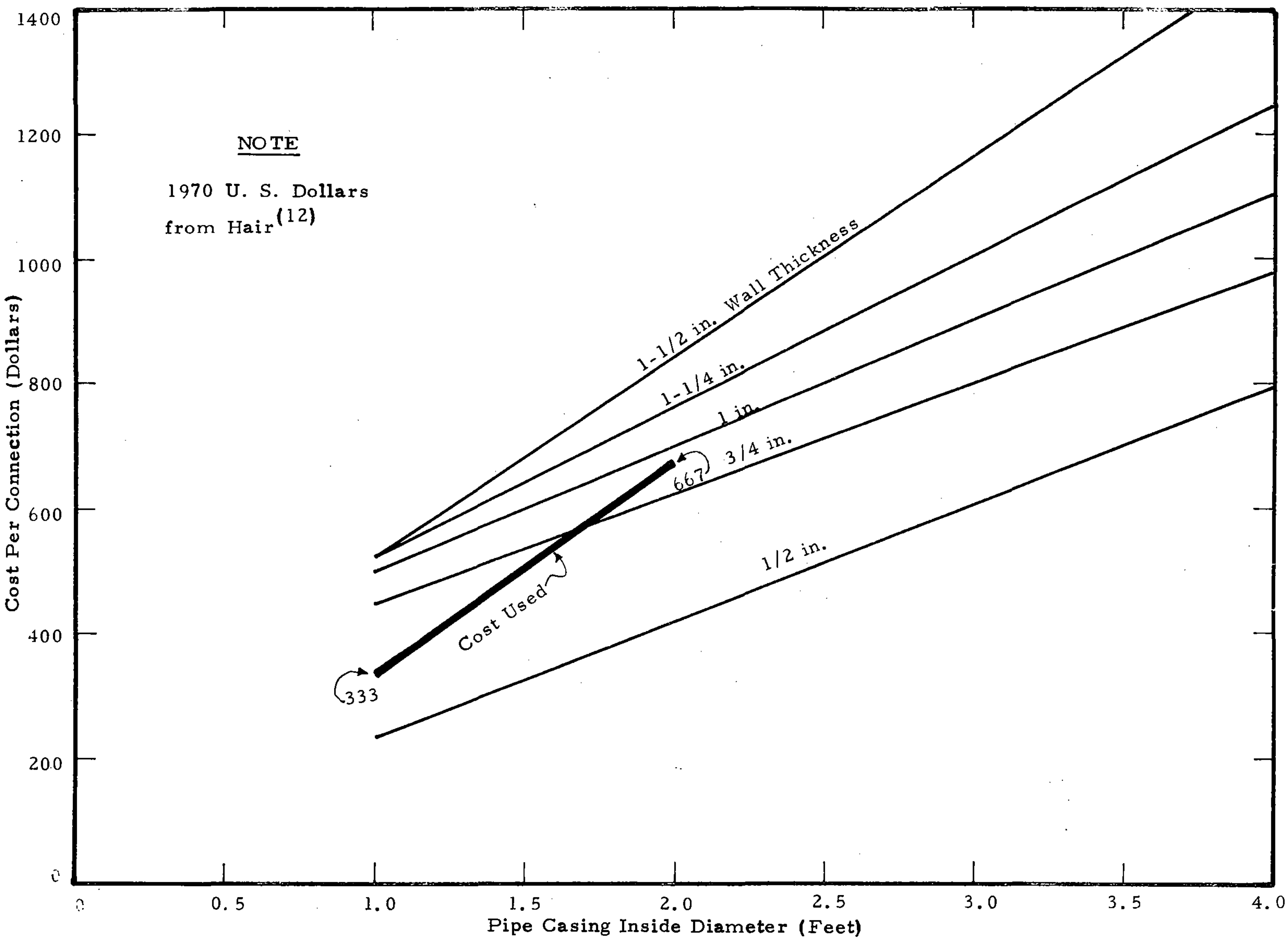

FIGURE 3B-43

PIPE CASING, WELDING COST
(After Hair[12])

Computation of energy costs is complicated by recovering energy from the return water, efficiencies, and the subtraction of an allowance of 500 feet of head for moving the return water in the horizontal transport leg. The hydraulic horsepower available for recovery, as a function of lifting horsepower, is estimated to be

$$HP_R = HP\left(\frac{D_1 - 500}{D_1}\right)\left(1 - C_w\right)0.80$$

0.80 = hydraulic to mechanical recovery efficiency.

The energy required to lift the slurry becomes

$$HP_E = HP\left(1 - HP_R\ 0.8\right)$$

where 0.8 is the efficiency to reconvert mechanical energy to hydraulic horsepower.

The energy cost becomes

$$\$/hr = HP_E \times 0.744 \times 0.015/0.64$$

where 0.015 is cost of electrical energy; 0.64 is efficiency of electro-hydraulic pump system; and 0.744 converts horsepower to kilowatts.

A 6-man crew is included for operation and maintenance of the system; pipe fitter rates are applied:

$$\$/hr = 6 \times 9.63$$

Operating and equipment costs are summed separately and ratioed with the capacity and lift height of the system.

System Cost/Performance - Figure 3B-44 presents specific operating costs for representative overall lift heights and mixture ratios. Figure 3B-45 presents similar data for equipment costs. In order to accurately present these variations in cost in the integrated system model, both depth and capacity are used as independent variables.

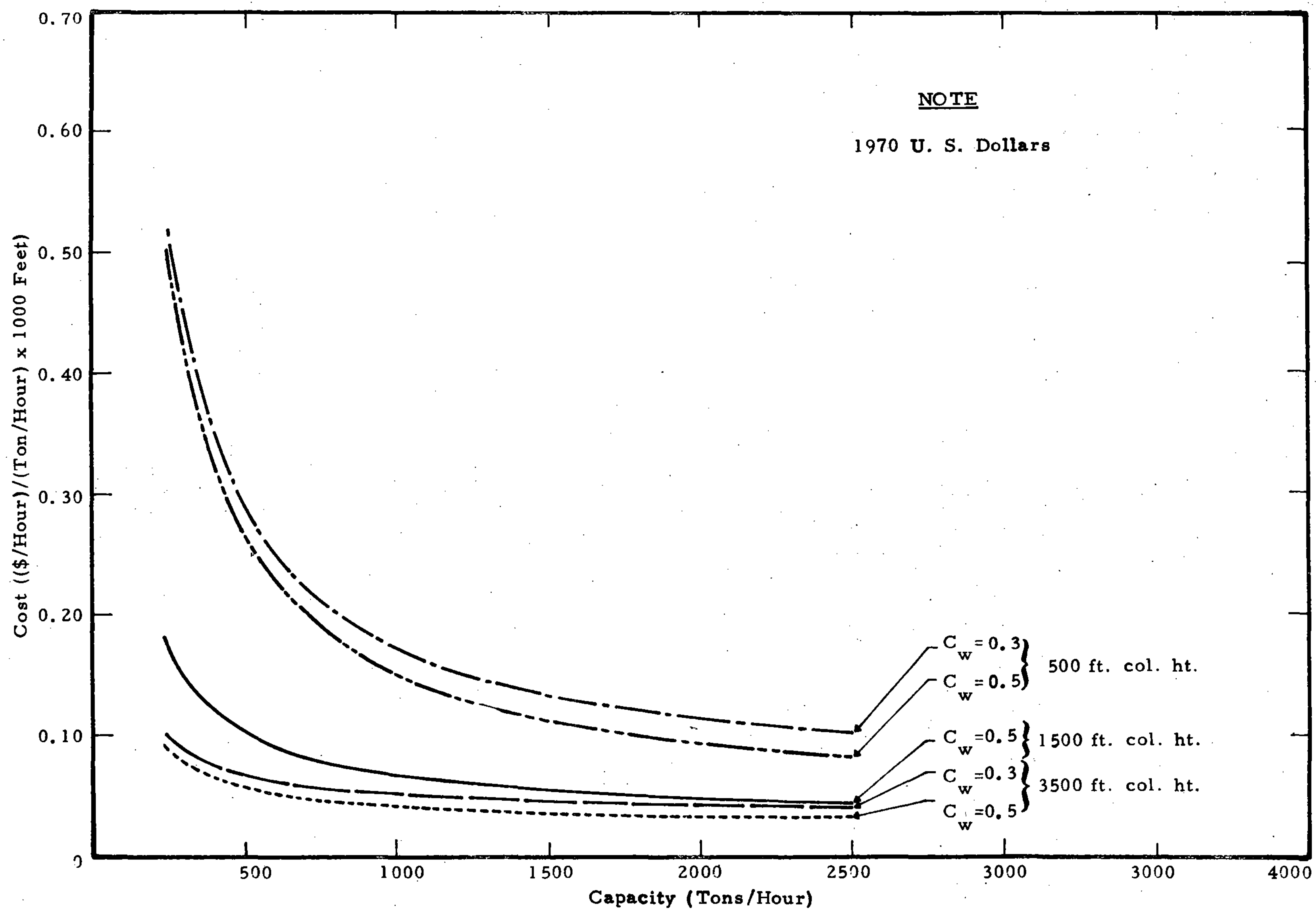

FIGURE 3B-44

HYDRAULIC SYSTEM (Vertical) OPERATING COST

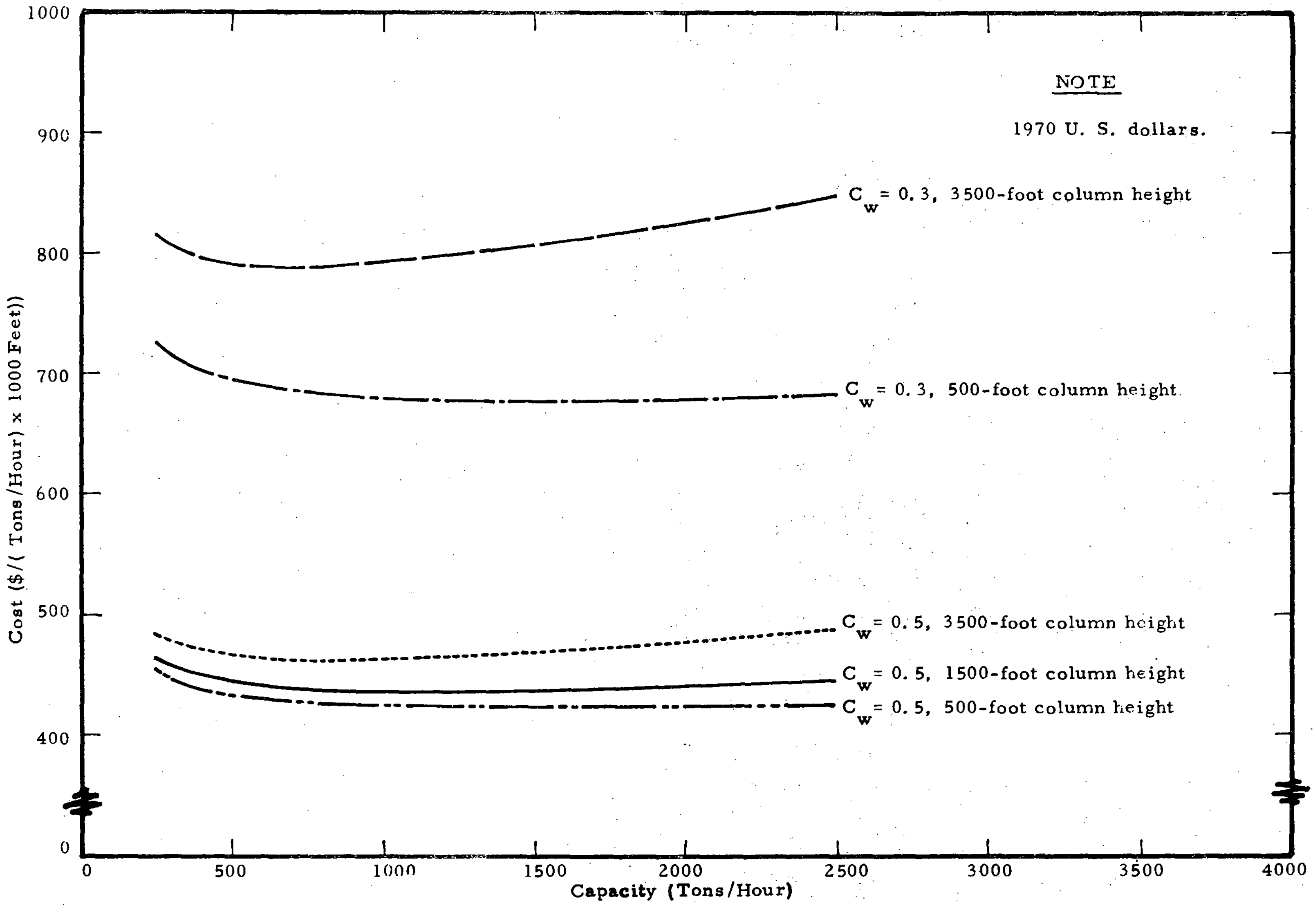

FIGURE 3B-45

HYDRAULIC SYSTEM (Vertical) EQUIPMENT COST

HOIST SYSTEM

The skip hoist, in one of several design forms, can be utilized to transport muck in the required quantities. For flow rates in excess of 1,000 tons per hour, data from actual installations were difficult to establish; therefore, data from 1,000 ton-per-hour systems are extrapolated to cover the required range.

Performance

The performance model for skip hoists computes cycle times for various shaft lengths by establishing the distance required for acceleration and the distance traversed at top speed. Acceleration and deceleration times are input as fixed quantities and are assumed to be equal. The top speed of skip hoists is characterized by its relationship to the height of the shaft. When the velocity is in feet per minute and the shaft height is in feet, they are numerically equal.

$$V_1 = L = \text{top velocity (feet per minute)}$$

$$A_1 = 0.000278\ L/T_5$$

where

T_5 = acceleration and deceleration time in minutes (0.25 minutes each)

L = distance in feet

A_1 = acceleration or deceleration in feet per second^2

The distance required to accelerate and decelerate is then computed assuming A_1 is constant.

$$L_1 = 1/2\ A_1\ T_5^2 = L_2$$

where L_1 is time to accelerate, and L_2 is time to decelerate.

Hence, the time at top speed is given by the equation

$$T_3 = \frac{L - \left(L_1 + L_2\right)}{V_1}$$

The cycle time for a single skip is equal to

$$T = T_3 + 2T_5 + T_8$$

where T_8 is the time to unload or load. Since the balanced hoist loads and unloads simultaneously, only a single load/unload period, T_8, is added to the cycle time.

The maximum rope pull is approximated by taking the product of the bucket capacity, material density, and the gross to payload ratio which includes an allowance for cable weight.

$$W_3 = C \times 1.75 \times 1.75 \times 2{,}000 \times 1.1$$

where

W_3 = the rope pull (pounds)

C = the capacity (cubic yards)

1.75 = the conversion from cubic yards to tons

1.75 = gross to payload ratio

1.1 = excess loading due to acceleration.

The average horsepower is then computed based on payload weight only since bucket and cable weight is fully counterbalanced:

$$HP = \frac{C \times 1.75 \times 2{,}000}{33{,}000\,\eta} \frac{L}{(T - T_8)} (1.1)$$

where η, the combined electrical and mechanical efficiency, is 0.6.

The delivery capability of the skip is

$$\text{tons/hour} = \frac{C \times 60}{T} .$$

The performance, as described by these equations, is based on constant use of the system in cycles of time length T (i.e., no slack time has been allowed). A loading and unloading time of 30 seconds must be maintained. This requires a high degree of automation in handling both muck and incoming material.

Cost

Equipment Costs - The major item in the equipment cost is the hoist unit. Reference 13 provides data on a series of hoist units of appropriate configuration and size to meet the material handling capacity requirements of the study. Costs related to horsepower for these units are:

Horsepower	Cost (1970 U.S. Dollars)
500	155, 000
1, 000	285, 000
2, 000	430, 000
3, 500	650, 000
6, 000	925, 000

The expression which fits these data is

$$C_1(\$) = 1999.8 \times HP^{0.7078}$$

Installation costs are included in the integrated system model.

Bucket costs are based on construction estimates of \$1.50 per pound for steel weldment for two buckets,

$$C_2(\$) = C \times 1.75 \times 0.75 \times 1.50 \times 2 .$$

The total cable costs are approximated by

$$C_3(\$) = 4\left(L + 50\right)\left(1.05\right)\left[-1.92 + \left(\frac{W_3}{2,000}\right) 0.0267\right]$$

(Safety factor of four)

where $(L + 50)(1.05)$ = feet of cable with allowances for wraps and other requirements. The remainder of the expression is for the cable costs which are estimated from Figure 3B-46.

The shaft guide rail costs are estimated to be

$$C_4(\$) = 50(\$/ft)(2L) .$$

The total equipment costs are the sum of the above quantities

$$C = C_1 + C_2 + C_3 + C_4$$

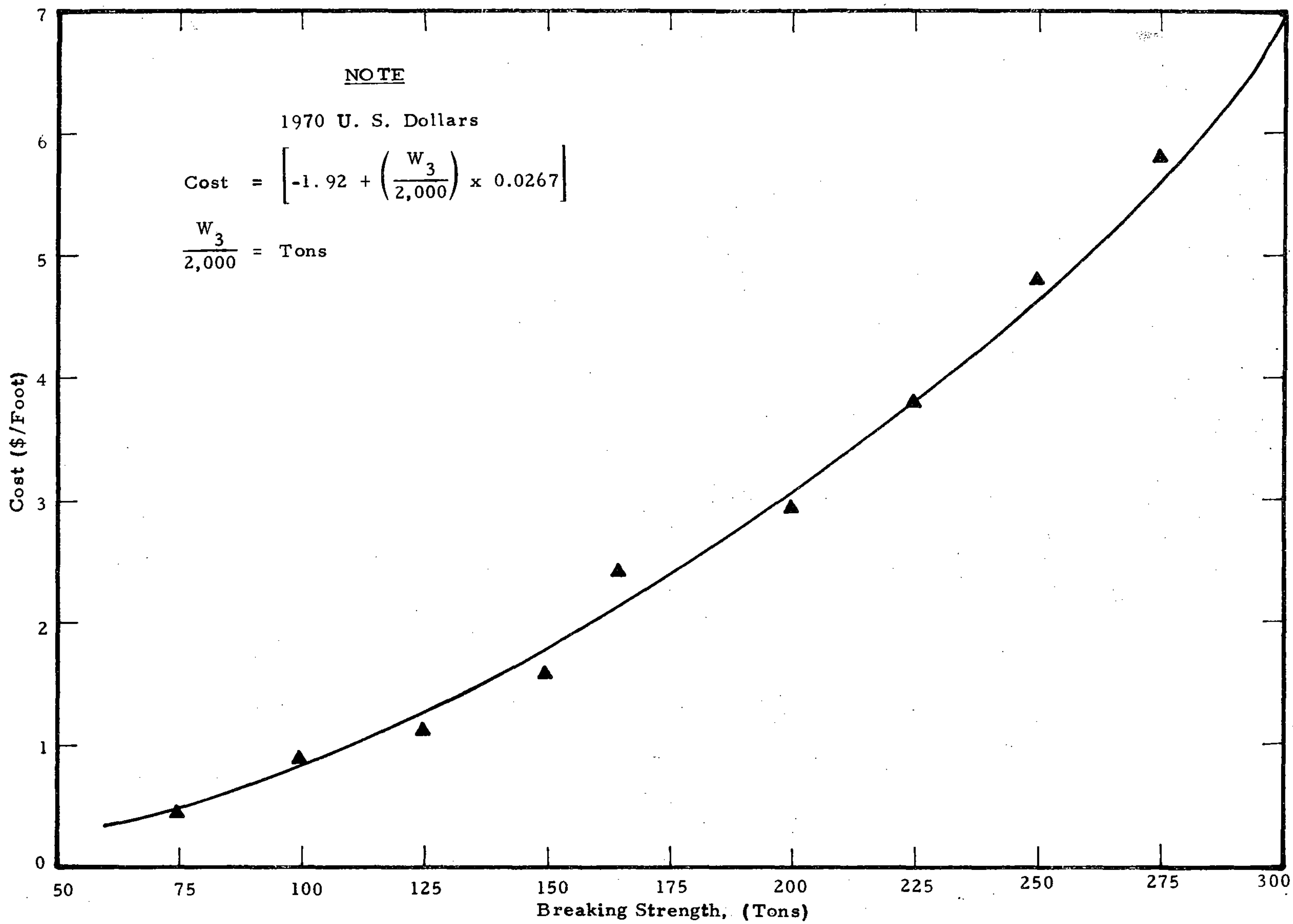

FIGURE 3B-46

HOIST SYSTEM, CABLE COST

Operating costs are based on a crew of six and electrical power at 0.015 per kilowatt,

$$C_5(\$/Hr) = 6 \times 6.75 + HP \times (0.015) \times (0.744) .$$

System Cost/Performance

Figures 3B-47 and 3B-48 present specific equipment and operation costs for skip hoists operating at various capacities and depths.

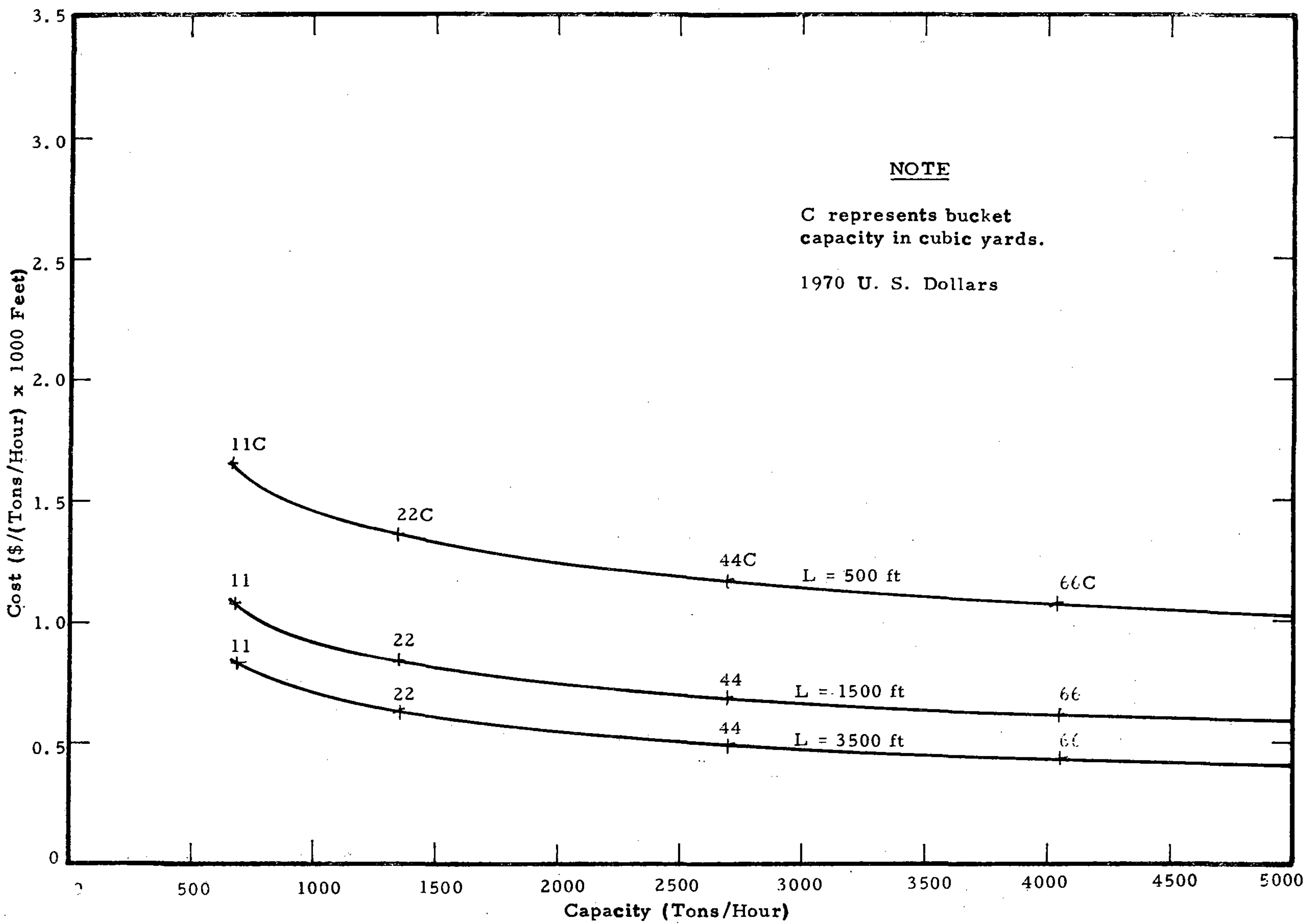

FIGURE 3B-47

HOIST EQUIPMENT COST

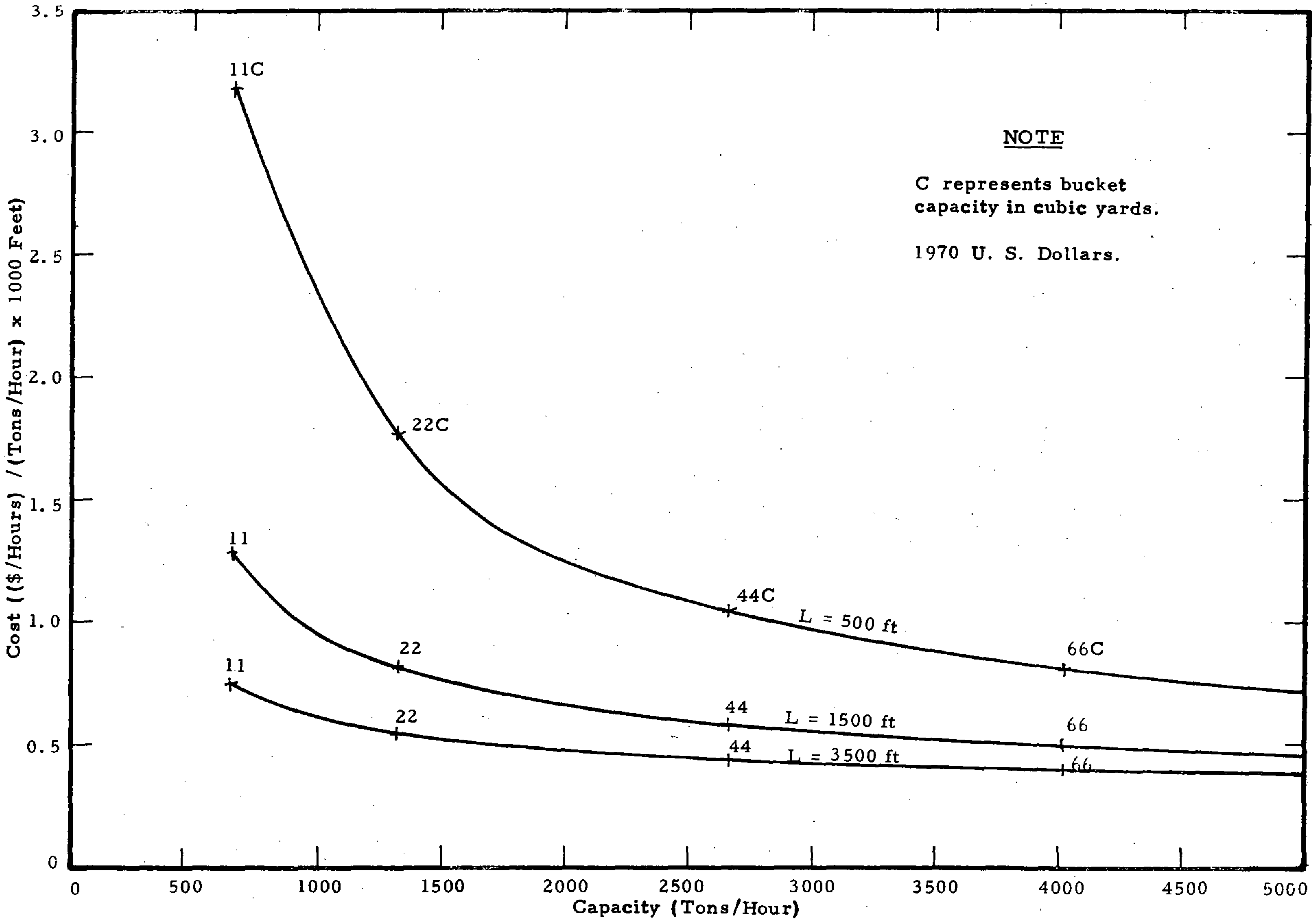

FIGURE 3B-48

HOIST OPERATING COST

CABLE DRIVE SYSTEM

The cable drive system concept described in Chapter 4 provides a means of assisting conventional rail cars, and perhaps trucks up an incline at speeds consistent with the material handling requirements of a high advance rate tunneling project. It is assumed that the hoist equipment used for this type of system is an adaptation of skip hoist equipment and can be operated continuously. The analogy between this system and the skip hoist holds throughout, although the performance and cost models are adjusted to reflect individual differences.

Performance

The performance model assumes that conventional rail cars arrive at the bottom of an inclined shaft at a fixed rate consistent with material handling requirements and car capacity. This can range from one car per minute to one car every 4 minutes.

The car velocities are computed from the rule of thumb,

$$V_1 = L \times P$$

where

L = horizontal projection of incline,

P = percentage of incline, and

V_1 = velocity in feet per minute, both directions.

Note that velocity is proportional to the depth of the tunnel, consistent with that assumed for vertical hoists. The car velocities in both directions (up and down) are assumed to be equal, which allows balanced system concepts for determining horsepower requirements.

The cycle time for lifting each car is computed by summing time increments:

$$T = T_5 + T_6 + T_3$$

where

T_3 = $(L - 2L_1)/V_1$, where L_1 = distance to accelerate,

T_5 = time to accelerate, and

T_6 = time to decelerate.

The number of cars being lifted at any one time is expressed by the ratio of the cycle time with the car feed cycle time (T_7) rounded up to the nearest integer, $N = T/T_7$.

The cable tension is computed by the expression

$$W = C \times 1.75 \times 2{,}000 \times 1.5 \times N$$

where

C = car capacity in cubic yards,

1.75 = tons per cubic yard,

2,000 = pounds per ton, and

1.5 = gross to tare ratio for conventional rail cars.

The horsepower is computed by

$$HP = \frac{1.1 \times N \times C \times 2{,}000 \times 1.75 \times L \times P}{T_7 \times 33{,}000 \times 0.6}$$

where 1.1 allows for friction losses and 0.6 is the combined mechanical and electrical efficiency.

The capacity of the system (continuously fed) is equivalent to

$$\text{tons/hr} = \frac{C \times 60 \times 1.75}{T_7}$$

Cost

The hoist and cable costs are computed based on relationships established for the skip hoist subsystem. Track costs and additional rail car costs are established based on equations developed for the locomotive drive system.

The crew requirement is estimated to be six men, and power costs are included by a method similar to that applied for skip hoists. One difference between this system and the skip hoist is the horsepower duty cycle. The skip hoist is only lifting approximately 75 percent of the time, assuming clock-like scheduling. This system would be loaded 100 percent of the time, although not necessarily to capacity. Ideal scheduling of returning cars (balancing the system) has been assumed for the purpose of this study.

System Cost/Performance

Figures 3B-49 and 3B-50 present specific cost data for the cable drive system.

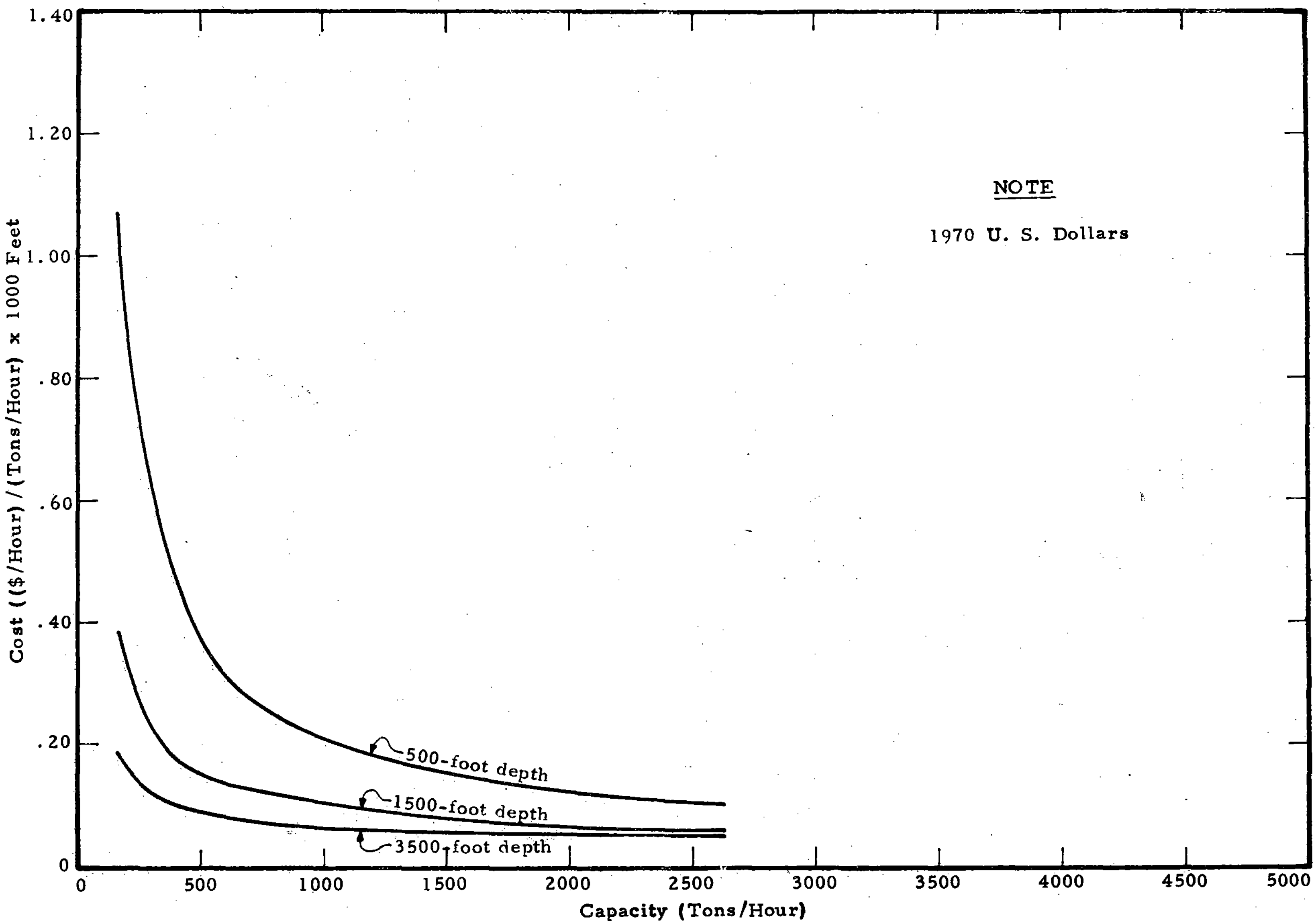

FIGURE 3B-49

CABLE DRIVE SYSTEM OPERATING COST

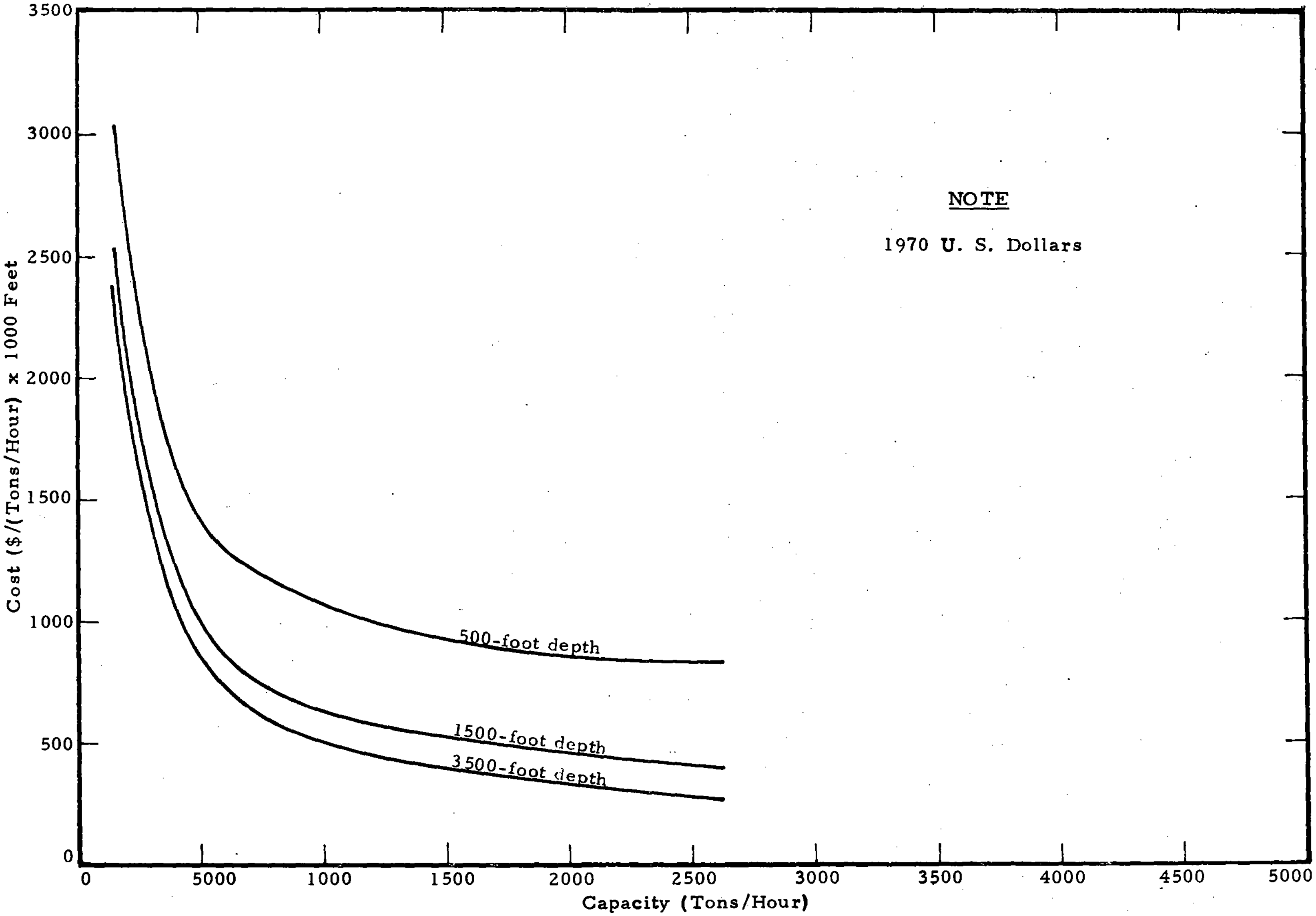

FIGURE 3B-50

CABLE DRIVE EQUIPMENT COST

SIDERAIL SYSTEM (Vertical)

The equations which represent the use of a rack and pinion drive in vertical applications are an extension of those used to represent the horizontal modular system. For a given car capacity (or car weight) the vertical lift speed is directly related to the horsepower developed in vertical lift. For electric motors, the horsepower developed in vertical lift for a short period of time can be much higher than the average horsepower capability of the motor. The torque of the motor and the current drawn will build up to match the load at a reduced speed. The losses of the motor, which appear as heat, may be greater than the motor can safely dissipate under a constant duty cycle of overloaded conditions. Siderail systems have been designed to operate both in vertical and horizontal runs. When the horizontal run is long compared to the vertical run, the duty cycle of the motor averages to an acceptable level; and, in essence, the motor cools off in the horizontal run. In the cases studied here it was desired to present a system which could run indefinitely in vertical trains lifting loads upward and returning, usually empty. Since it was anticipated that the 1-cubic-yard cars with 30 horsepower motors would not move material through a shaft fast enough to meet most requirements, the system model was designed to increase the horsepower in steps of 30 horsepower. The transmission was assumed to be adequate for up to 180 horsepower. The cycle time was computed similar to the method employed in the truck model (i.e., the acceleration time was used as a constant).

The time to travel the vertical leg at top speed was computed as a function of horsepower using the equation

$$T_3 = \frac{60(L - 2L_1)(5{,}500 + H_1 \times 20)}{H_1 \times 0.72 \times 33{,}000 \times 1.5}$$

where

L = total shaft length (feet)

L_1 = distance to accelerate or decelerate

H_1 = the horsepower per module

5,500 = loaded weight of the module less motor

20 = approximate weight (pounds) of motor per horsepower

0.72 = unit efficiency

33,000 = 1 horsepower in foot-pounds per minute

1.5 = overload factor of the motor while climbing

T_3 = the time (in seconds) to climb the vertical leg

T_4 = the time to return at constant velocity (assumed to be equal to T_3)

Computations for the performance capacity of the system are similar to those applied in other systems. Power regeneration was not considered.

Cost

The cost model reflects increased module costs for increased horsepower as follows:

$$\text{Module Costs} = (4{,}000 + H_1 \times 30)N$$

where N = number of modules in the system.

$$\text{Shaft Track Costs} = 2L(45 + 8) .$$

Personnel and maintenance costs are the same as for the horizontal version of this system. Rack and pinion repair costs were assumed to be equal to tire costs in horizontal applications.

System Cost/Performance

Figures 3B-51 and 3B-52 present specific equipment and operating costs for the vertical siderail systems of varying capacity and shaft depth. In several cases analyzed, it was found that the number of low-powered modules required to meet a high capacity would not physically fit on the guideway. The cases shown are compatible in this respect.

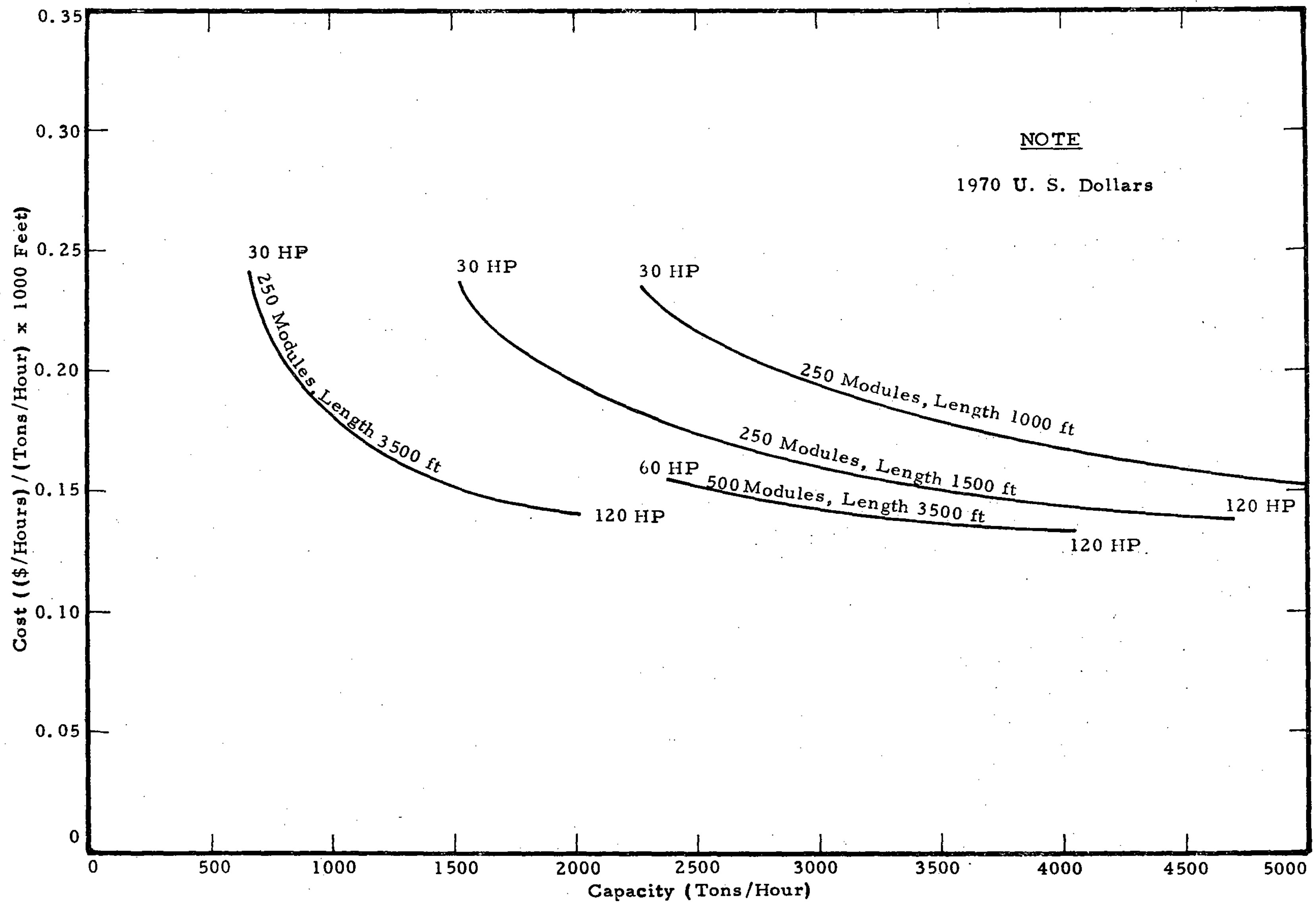

FIGURE 3B-51

SIDERAIL SYSTEM (Vertical) OPERATING COST

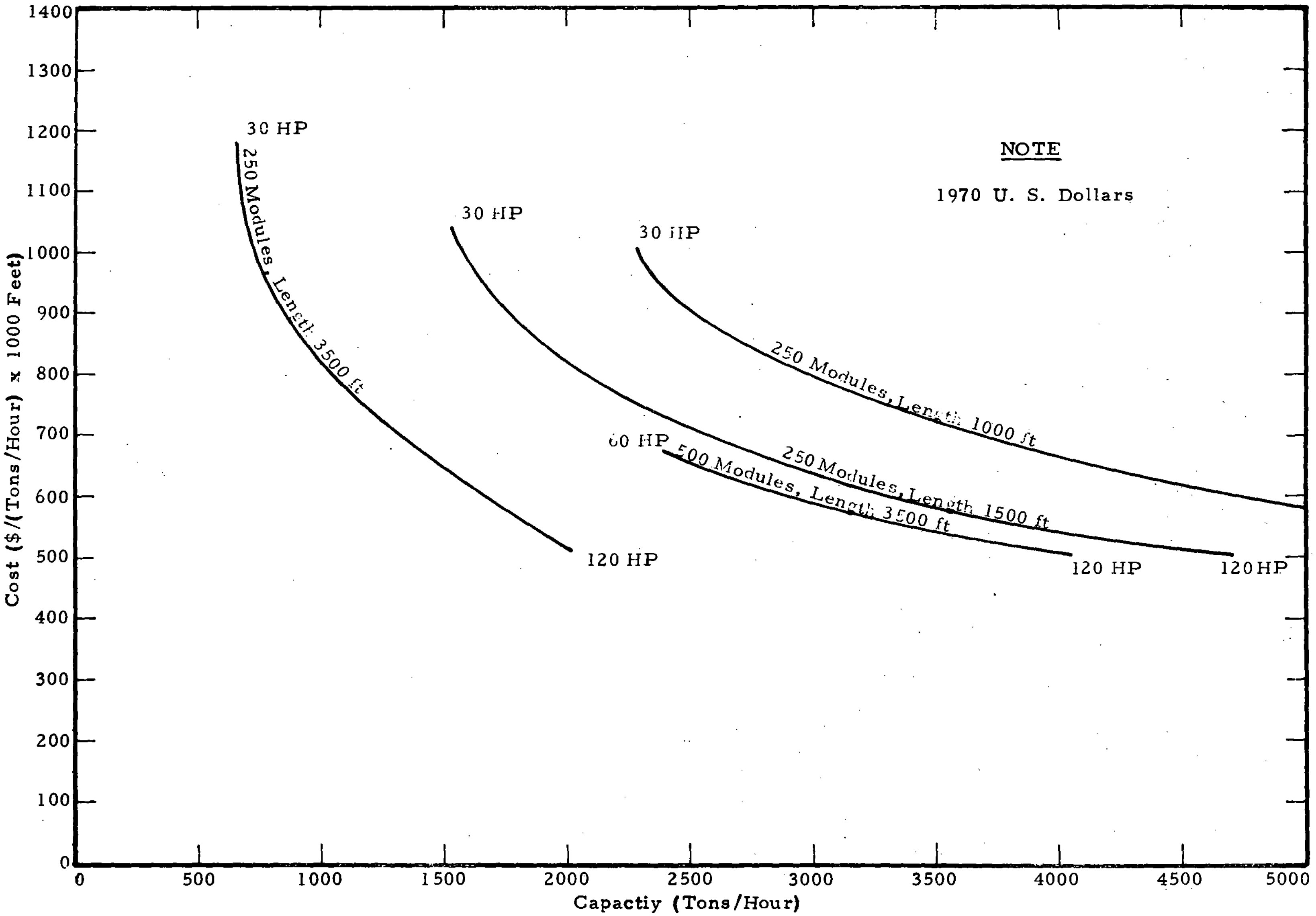

FIGURE 3B-52

SIDERAIL SYSTEM (Vertical) EQUIPMENT COST

MONORAIL SYSTEM

A number of similarities between the monorail system and the siderail system are noted:

1. The structures are similar to the extent that they are both supported by welded structural steel shapes.

2. Both systems require a rather complex carriage and gearbox mechanism.

3. Both systems are electrically powered from a continuous bus paralleling the track.

4. Both systems use rubber tires forced against the rail for traction.

5. Both are adaptable to automation; i.e., are generally considered to be unmanned and remotely operated.

Since these similarities exist, it is reasonable that the analysis of the monorail and siderail systems be performed in a similar fashion.

Performance

The system performance model is identical in form to the siderail performance model with respect to cycle time and performance computations. Loaded module speeds of 30 miles per hour and empty module speeds of 50 miles per hour were assumed. Car sizes and horsepower ratings have been adjusted to reflect the larger units proposed for the monorail.

Cost

The monorail system costs are also based on elements and equations similar in form to the siderail system; however, adjustments are made to reflect economies of scale for power units, modules, and unit length guideway costs. The unit costs used are those in Table 3B-2.

TABLE 3B-2

MONORAIL SYSTEM UNIT COSTS

Tunnel Diameter (feet)	Car Size (cu yd)	Power Unit ($/cu yd)	Guideway ($/ft)	Module ($/cu yd)
10	2	3,800	50	1,200
20	4	3,000	75	1,000
30	7	2,500	150	800
40	10.5	2,000	350	600

The monorail and rail structural support costs are major cost elements in this system. These costs, summarized under guideway costs in Table 3B-2, were developed from two cases.

Case	Tunnel Diameter (feet)	Car Weight (pounds)	Car Size (feet)
A	20	10,000	3 x 3 x 6
B	40	50,000	5 x 5 x 12

Ring support, cross member, and rail-beam structure costs for monorails are estimated to be $0.75 per pound for material, prefabrication, and installation. Structure weight estimates are:

	Case A (lb/ft)	Case B (lb/ft)
Monorail Tracks	96	156
Support Cross Members	18	70
Ring Segment	80	680
	194	906
Total Cost Installed ($/ft)	$145	$715

Based on these data points, an estimate of structure cost was developed from Figure 3B-53.

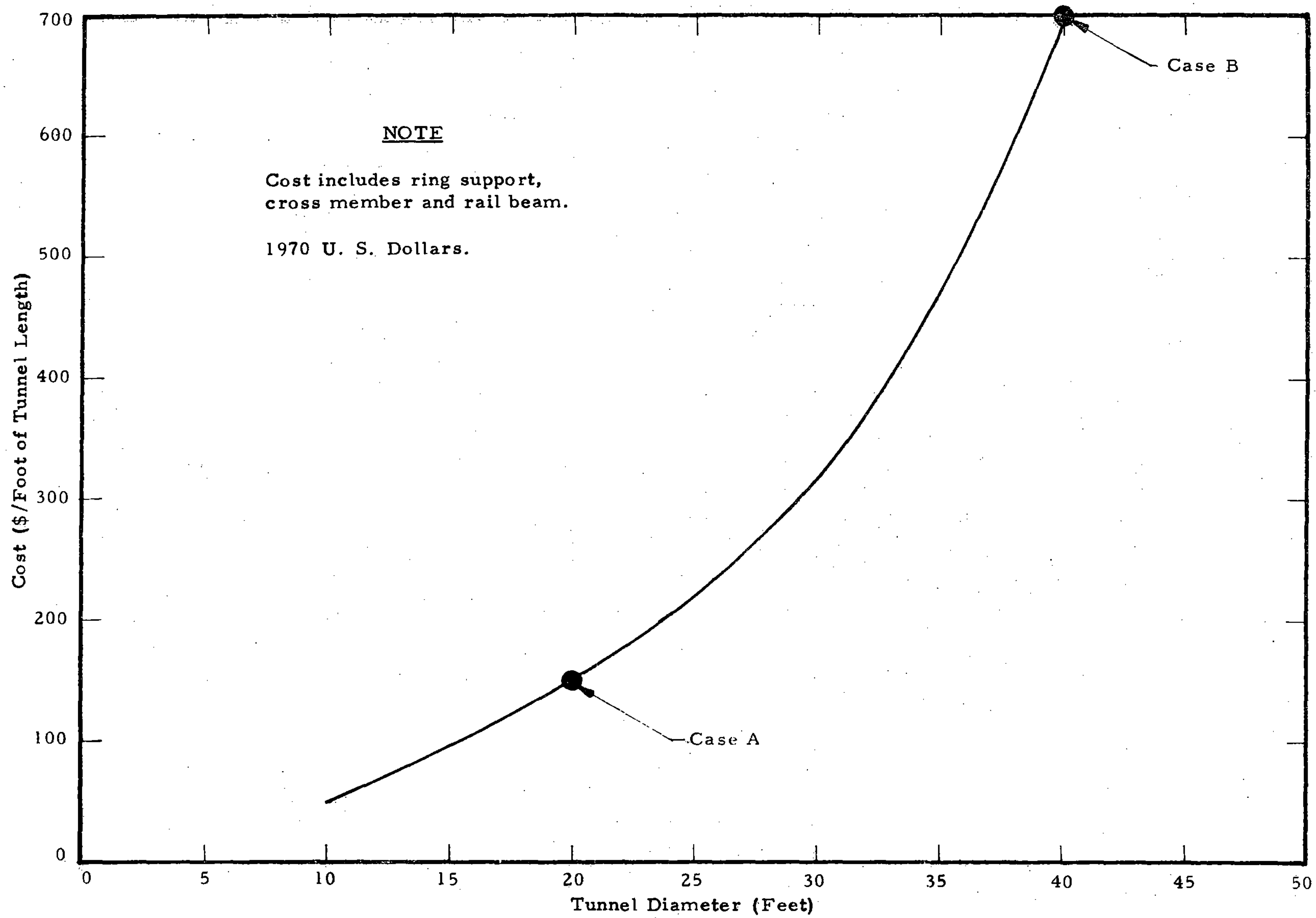

FIGURE 3B-53

MONORAIL SYSTEM STRUCTURE COST

It is evident that these costs will remain relatively constant with advance rate since the number of monorail trains, rather than module size, can vary as the advance rate varies. Module size sets the structural requirements. For analysis, one-half of the structural costs are allocated to material and prefabrication and included in the monorail equipment cost. One-half of the cost is assumed to be installation labor cost and is included in the system extension cost element.

System Cost/Performance

Figures 3B-54 and 3B-55 present specific operating costs and specific equipment costs for the monorail system concept used in this study.

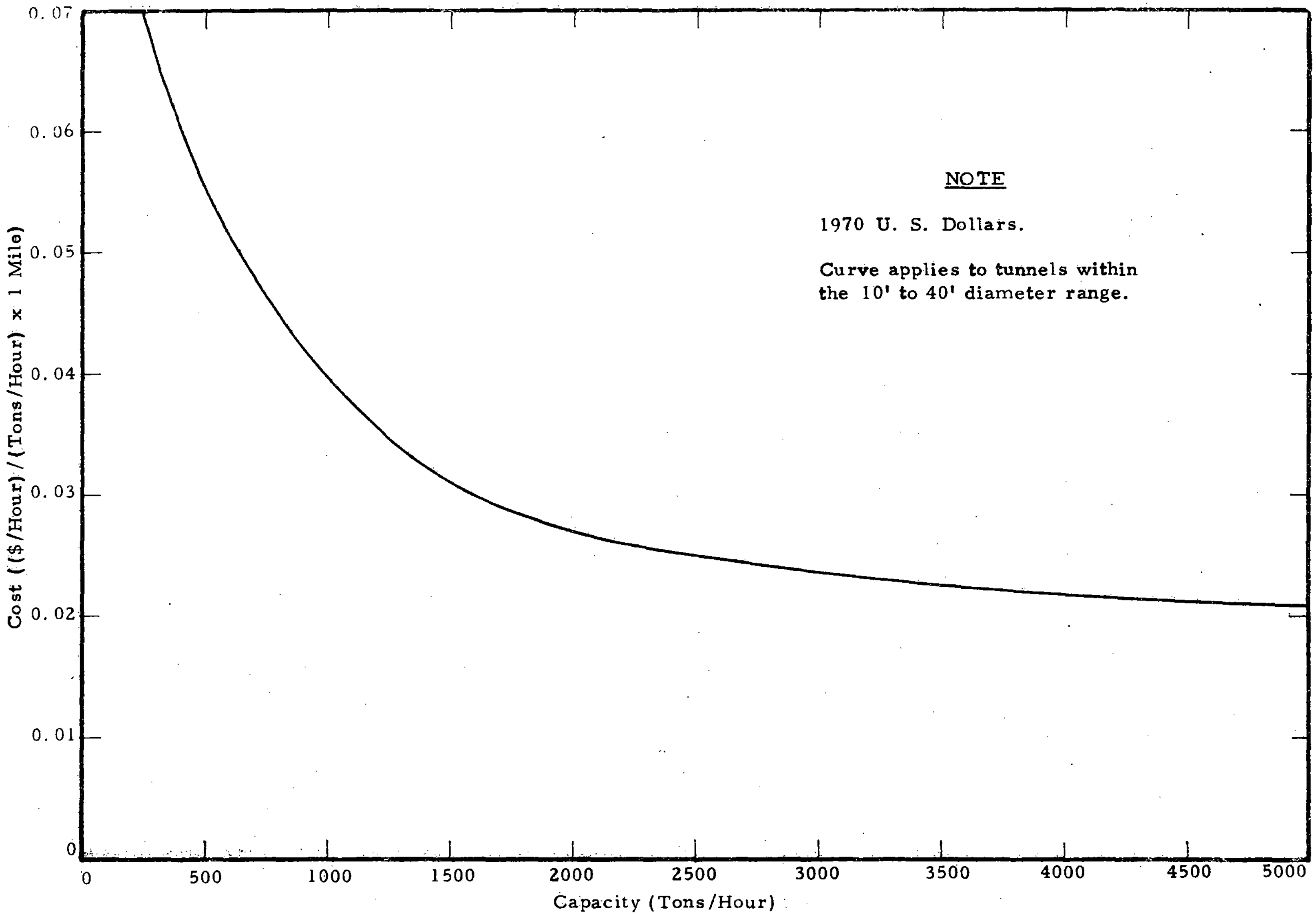

FIGURE 3B-54

MONORAIL SYSTEM OPERATING COST

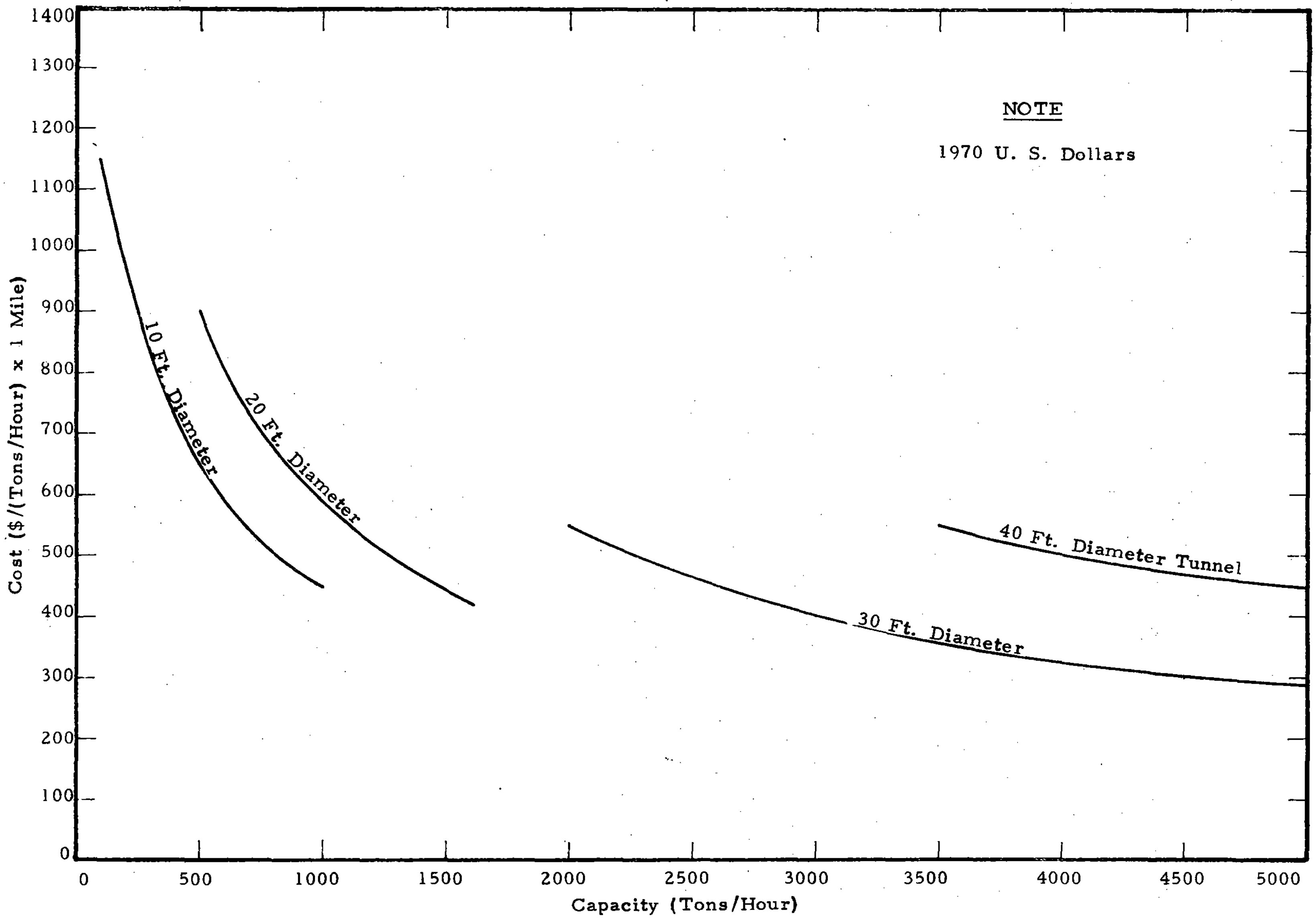

FIGURE 3B-55

MONORAIL SYSTEM EQUIPMENT COST

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PART 4:
RESEARCH AND DEVELOPMENT

CHAPTER 16

RESEARCH AND DEVELOPMENT NEEDS

Compared with recent efforts to advance the state of the art of excavation, little has been done to improve material handling systems for tunneling. The major efforts have been in the area of rock breaking. This is appropriate since excavation has in the past paced the construction of tunnels. Improved methods of handling both muck and incoming materials have not been required as existing methods have been adequate.

Major technical advancements in several excavation techniques which will make possible face advance rates far in excess of those within present capability are anticipated for the next decade. To obtain full advantage of the improvements in excavation, great improvement must also be made in material handling and other functions which support the excavation.

This study was conducted to identify the material handling requirements of the future, the material handling concepts which offer the best potential for meeting these requirements, and the developments which must take place to achieve practical systems. Since the achievement of increased face advance rates and increased material flow rates is a gradual process requiring many years, the relative cost/effectiveness of alternate material handling systems varies with system capacity, and the system alternates are in various stages of development, it is prudent to invest resources in the development of more than one system. This appears to be the best approach to the solution of short-term problems and gives greater assurance of timely development of adequate systems for long-term problems. The emphasis in staging the development program should be on bringing adequate systems to practical application at the time of need. This means focusing initial attention on those concepts which have potential to meet the progressively increasing requirements without unduly long development programs. More exotic concepts should be infused into the development program with the appropriate lead-time if concepts currently better developed appear to fall short of expectation as a result of further investigations and developments, or if a new concept shows greater potential. Present indications are that concepts well along in the development cycle are adequate to meet the material handling requirements of the future. The group of systems chosen contains simple mechanical approaches and the basic forms of pneumatic and hydraulic conveyance. In most cases, no attempt to date has been made to tailor these concepts to tunneling by an organized development program. This should be done before investing large sums in more exotic approaches.

RESEARCH AND DEVELOPMENT APPROACH

An orderly approach to systems development requires several sequential steps from identification of candidate systems to final full scale system demonstration in a true tunnel environment.

Step 1 - Selection

Identify the system or systems which appear to offer the best potential for timely development to meet the material handling requirements imposed by increasing advance rates. Also consider ability to perform at the least total life-cycle cost. This has been accomplished to a degree by the present study.

Step 2 - Analysis

Perform detailed analysis, trade-off studies and experimental design to identify problem areas in greater detail and develop specific developmental programs for their solution.

Step 3 - Prototype

Develop prototype hardware and operating procedures to demonstrate the material handling system(s) on a schedule which is consistent with the requirements of high advance rate tunneling, but at minimum development cost and risk. An outline for a material transport system specification is presented in Appendix 4A.

Step 4 - Implementation

Implement and demonstrate the system(s) chosen for development in simulated or actual tunneling situations in a manner that will:

- Show that cost and performance goals have been achieved.
- Encourage acceptance of the equipment and the system procedures until they become standard practice in the tunneling industry.

Throughout the developmental cycle emphasis should be on integrated development of the complete material handling system rather than separate elements or functions of the system.

Dual-mode systems may be developed mode by mode, but careful attention must be given to the allocation of space in the near-face zone; otherwise there may be interference between the modes when they are operated together. This type of complication is also present in a more critical form if single mode systems are developed for muck and incoming material under separate programs. The value gained from demonstrating a material handling system operating between two fixed points is limited since it ignores the problems of advancing the system. If the system is demonstrated in a simulated or actual tunnel environment, much can be achieved. Specialized equipment required in the near-face zone and shaft station should be developed as an integral part of the system or at least criteria should be established for the material transport system based on its interface with the special equipment.

Demonstration - Tunnel projects are continuously underway throughout the United States. They are driven in diversified areas and under various geologic conditions. In most cases these projects are being managed by highly skilled tunneling contractors who are vitally interested in any means to improve efficiency and further develop the industry. When the development of a new concept in tunneling is to be demonstrated it seems reasonable that these contractors, working with the equipment manufacturer and supported financially for extra costs by a sponsoring government agency, would provide the necessary ingredients for demonstration. By such an approach two additional goals could be accomplished. The tunnel construction industry would contribute its experience, playing an active part in the program; and geologic conditions most suited to the specific test or research problem can be selected.

An alternate approach to full-scale demonstration is the field testing laboratory. However, it is apparent that locating a suitable site with the wide range of rock conditions desired would be difficult.

SYSTEM REQUIREMENTS

The basis of selection of transport modes and specific problem areas for beneficial application of research and development resources is the potential offered by the alternate systems to meet the future requirements for material handling in tunneling projects at minimum cost. Although cost is a primary consideration, other factors such as performance potential of the transport mode and physical features bearing on the life cycle performance of the total system should be given consideration in the selection of targets for research and development effort.

Performance requirements for a material handling system to serve a rapid excavation tunneling project are discussed in Chapters 1, 2, 6, and 12. These requirements are summarized as:

- Transport attitude. Deep tunnels require one or more attitudes of material transport, from horizontal through inclined to vertical. A wide range of attitude capability provides flexibility for application of a transport mode in various situations and tends to reduce complexity of operation due to multimode transport, intermode transfer, and the need for highly synchronized operations.

- Materials capability. A wide range of materials must be transported to and from the work areas. These include bulk materials such as muck, discrete materials used in the construction process, equipment and personnel. The capability of a transport mode to carry all types of materials provides flexibility and perhaps reduces complexity of operation in some cases. However, problems of synchronized loading and unloading in the near-face zone may be more severe if all materials are carried by a single mode.

- Compatibility with limited cross section, single route access, and tunneling operations. At best, space limitation is a severe constraint on tunneling operations; in smaller tunnels this constraint can become the major factor in selection of operational methods. Minimum cross section becomes an extremely important consideration in system selection. The constraint of single route access requires turnaround or direction reverse of vehicles in a unitized system. Direction reverse requires cross-over switching for a high capacity, dual guideway system. Compatibility with other tunneling functions is critical, particularly in the near-face zone. Transport systems requiring excessive space due to vehicle size or auxiliary equipment tend to interfere with other tunneling operations.

- Flexibility to accommodate special requirements such as variation in muck quantities and characteristics due to changing ground conditions, variable construction material characteristics and flow rates, intermediate loading and unloading points, and the need for simultaneous, continuous, high rates of material flow. A deficiency in any one of these requirements could severely limit the tunneling process, particularly when unanticipated situations occur due to unpredicted ground conditions requiring a change in excavation or ground support method after initiation of excavation.

- Availability. A high degree of system reliability is required to assure a large availability factor. The cost/performance ratio increases rapidly as downtime increases.

- Safety. System safety is an important consideration in comparing transport modes. The cost of modifications to provide systems with equivalent levels of safety should be included for final system selection.

- Long life. A rugged transport system is necessary to provide a reasonably long system life and large amortization base for the capital cost. A rugged system also tends to have a lower frequency of repair, thus reducing downtime and maintenance cost.

- Easily installed, dismantled, moved, and reinstalled. Reduced time and cost for these elements of the system life cycle are important to achieve minimum tunnel project cost.

- Easy system extension. The ability to continuously extend the horizontal transport system with minimum or no interruption of material flow is essential to achieve very high rates of face advance.

- Suitability for system automation. To achieve the continuous high rates of material flow desired and the required synchronization with other operations, the need for a high degree of automation is anticipated. Systems inherently suited to this mode of operation are desired.

- Low maintenance frequency and cost are desired to reduce downtime and operating cost.

- Minimum auxiliary material handling equipment at the near-face zone and shaft station are desired to reduce the space requirement, complexity of operations, and capital investment.

SYSTEMS EVALUATION

System characteristics of the transport modes investigated were evaluated in relation to the system performance requirements. In the attempt to project system capabilities into the future, considerable engineering judgment was applied in assessing the system potential for development. Factors indicating performance potential and physical features for the various transport modes are summarized in Table 16-1. The purpose of this evaluation is to provide a basis for identification of areas of research and development need; it is not directed to the selection of a particular material handling method for application in a current tunneling project.

A qualitative summary of systems costs, based on integrated systems data presented in Chapter 15 and cost/performance data presented in Chapter 13, is given in Table 16-2.

Horizontal Transport

The systems physically suitable for horizontal transport are:

- Truck
- Locomotive Drive
- Side-Wheel Drive
- Siderail
- Monorail
- Conveyor
- Hydraulic
- Pneumatic

Operating and equipment specific costs for these systems are compared in Figures 13-3 and 13-4. In the capacity range from 1,000 tons per hour to 5,000 tons per hour, the locomotive drive, side-wheel drive, and hydraulic systems appear to have the lowest specific costs. Truck and conveyor systems appear to be somewhat more costly. The siderail and monorail systems appear to be the most expensive except for the pneumatic which has operating costs 10 to 100 times as great as the other systems.

TABLE 16-1

SUMMARY OF SYSTEMS CHARACTERISTICS

Key: A = Average; Blank = No; D = Difficult or Complex; E = Easy or Less Complicated; G = Good; L = Limited; NA = Not Applicable; P = Poor; Q = Questionable; ● = Yes

Characteristics	Unitized Systems							Continuous Systems		
	Truck	Locomotive Drive	Side-Wheel Drive	Cable Drive	Siderail	Monorail	Hoist	Conveyor	Hydraulic	Pneumatic
PERFORMANCE POTENTIAL										
Horizontal Transport	●	●	●		●	●		●	●	●
Inclined Transport			L	L	●	Q	●	L	●	●
Vertical Transport			Q		●		●		●	●
Transport Bulk Materials	●	●	●	●	●	●	●	●	●	L
Transport Discrete Materials	●	●	●	●	L	L	●	L		
Transport Equipment	L	●	L	●	P	P	●			
Transport Personnel	●	●	●	●	●	●	●			
Compatible with Limited Cross Section	P	P	A	A	A	A	A	G	G	G
Compatible with Single Route Access	P	A	A	NA	P	A	NA	G	G	G
Compatible with Other Tunneling Functions	P	P	A	NA	A	A	NA	G	P	G
Accommodate Special Muck Conditions	L	G	G	G	G	G	G	P	G	G
Accommodate Variations in Flow Rate	G	G	G	G	G	G	P	A	P	A
Accommodate Intermediate Loading Points	G	G	A	NA	A	P	NA	A	P	A
Accommodate Bidirectional Flow	P	A	A	A	G	A	P	L		
Reliability/Availability	G	G	A	P	G	A	G	P	A	P
Safety	Q	A	A	Q	G	Q	G	A	Q	G
PHYSICAL FEATURES										
Rugged (Long Life)	A	G	A	P	A	A	A	P	G	P
Installation	E	A	E	D	D	D	A	A	A	E
Dismantle, Move, and Reinstall	E	E	A	D	D	D	A	A	D	A
System Extension	E	A	A	NA	D	D	NA	D	D	E
System Automation	D	E	E	D	E	E	E	E	E	A
Maintenance	A	G	G	D	A	D	A	D	D	D
Material Handling at Near Face	D	E	A	NA	D	D	NA	E	D	A
Transfer Equipment at Shaft	D	D	E	A	E	D	A	E	A	E

TABLE 16-2

SUMMARY OF SYSTEMS COSTS

Key:
A = Average
Blank = Not Applicable
H = High
L = Low
NR = Not Run
A/L = {Average at 1000 T/hr; Low at 5000 T/hr}
(A/L) = {Average for D = 10, D_1 = 500; Low for D = 40, D_1 = 3500}

Cost Item	Unitized Systems							Continuous Service		
	Truck	Locomotive Drive	Side-Wheel Drive	Cable Drive	Siderail	Monorail	Hoist	Conveyor	Hydraulic	Pneumatic
Integrated System Cost	(L/A)	(L/L)	(L/L)	(L/L)	(H/H)	(L/H)	(L/A)	(A/A)	(L/A)	NR
Muck Disposal at Surface	L	A	A	A	H	H		A	H	H
Horizontal Transport										
Operating Cost	A/A	A/L	L/L		H/A	A/A		A/A	L/A	H/H
Equipment Cost	L/A	A/L	A/A		A/A	H/H		A/A	L/L	H/H
Inclined Transport										
Operating Cost			L/L	A/L				A/H		
Equipment Cost			H/A	H/A				A/A		
Vertical Transport										
Operating Cost					H/H		A/L		L/L	A/A
Equipment Cost					H/H		H/H		A/H	L/L

Trucks - The major advantage of trucks is the flexibility obtained and the low roadbed preparation cost. This results in low equipment cost in the low capacity range (below 1,000 tons/hour). The poor compatibility with the tunnel environment and difficulty of automation work against the use of trucks, particularly in small tunnels. Specially designed underground trucks are in use but even these occupy relatively large volumes in relation to the volume of the payload. In the higher capacity ranges, several other systems have lower operating and equipment costs.

The problems of overcoming the unfavorable ratio of total space requirement to payload volume, and guidance and control at the speeds required for rapid excavation, provide little attraction for further development of the transport mode except for special situations.

Locomotive Drive - These systems exhibit more favorable operating and equipment costs as the capacity requirement increases above 1,000 tons per hour. Below this capacity the system costs become increasingly unfavorable. The locomotive/hoist and locomotive/cable drive combinations exhibited integrated system costs among the lowest of those determined for an advance rate of 300 feet per day. At higher advance rates, more favorable costs would be expected for this system. In circular tunnels roadbed preparation costs will offset some of the apparent cost advantage. In small tunnels, this system has an undesirably large space requirement. Other performance and physical features of the system appear to be average or better than average.

Side-Wheel Drive - The side-wheel drive system uses a conventional rail guideway system, but is propelled by a unique drive system which overcomes some of the disadvantages of the locomotive drive such as the large cross-section requirement, low traction, and high operating cost at low capacity. The side-wheel drive exhibits the lowest operating costs of all systems in all capacity ranges. Its equipment costs vary from 10 to 30 percent greater than those for the locomotive drive.

With further development of the vehicles, it is anticipated that the system can handle both muck and incoming material and can be sized to meet all anticipated requirements. It has the potential to transport men using either the basic system concept or self-propelled cars on the same guideways. The prototypes which have been developed are automated. Roadbed requirements are minimal compared with the locomotive drive system. Narrow gauge mine track can be used for the guideway. The load is distributed over long lengths of track as opposed to the concentrated load required to insure traction for a locomotive. The improved traction allows this system to ascend rather steep inclines. For use on inclines, the power can be increased to match the work necessary to meet the material transport requirements. Reduced levels of power can be installed in level tunnel sections. The side-wheel drive is a simple mechanical device, yet it represents an innovative approach with good possibilities of economic advantages.

Fundamental considerations dictate that vehicles be small and that train lengths be long. This configuration matches the tunnel space. In general, The concept appears to be one of the most flexible in adaptability to special and variable conditions.

The availability potential seems high since a portable power traction unit could be designed to minimize downtime due to power unit failures. The prototype models use light-weight cars which might be susceptible to damage in a tunneling application, but there is no apparent reason why more rugged cars could not be used. Wider track gauges and special cars will be required for large liner segments.

The drive system is relatively simple and should be reasonably trouble-free. The drive mechanism, pneumatic tires, and vehicle steel wheels will require occasional replacement. These appear to be the major itms of maintenance cost.

System installation, dismantling, and moving appear compatible with tunnel operations. It is anticipated that power units could be fabricated into easily transported sections and require very little foundation preparation prior to installation. The light gauge mine track can be assembled in prefabricated sections for rapid installation. System extension, dismantling and moving would be no more difficult than the initial installation.

The side-wheel drive mode of transportation could also be used for muck disposal on the surface, thus requiring no intermode transfer. If inclined shafts are available, the same mode can be used for muck transport from the near-face zone to the point of disposal.

The major disadvantages of the side-wheel drive system are:

- If incoming material and muck are handled by the same system, scheduling in the near-face zone is more complicated than if a dual mode system is used.

- The power units are activated only when trains are passing through the power unit. This can result in low utilization of the investment in power units.

- Only standard length trains can be used since they must bridge between the power stations.

Siderail - In the lower capacity range (up to about 1,500 tons/hour), the siderail system operating costs are the highest of any system investigated except the pneumatic pipeline. As the capacity increases and assuming the use of larger vehicles, the siderail shows more favorable operating cost, dropping about 30 percent below the conveyor and about equal to trucks and monorail.

The equipment cost for the siderail system also becomes more competitive in the higher capacity range. It groups with the conveyor and sidewheel drive just above the locomotive drive. In the lower range, the siderail system has the highest equipment cost except for the monorail and pneumatic systems. This high equipment cost appears to be due to the structural support and rail configuration required for the siderail concept and the self-propelled, automatic-closing modules used. A value engineering and design program directed to cost reduction might make significant reductions in equipment cost.

Because of the support at the sides of the vehicles and the vehicle design, the siderail system in its present configuration is limited in its ability to carry large irregular-shaped materials and equipment. Cross-over switching appears to be somewhat more complex for this system than for conventional rail systems.

The high degree of stability provided by this concept makes it outstanding for simultaneous, bidirectional, high-speed travel in confined space. The reliability and safety of the system also appear to be good. The system appears to be ruggedly constructed but will probably be more difficult to install, dismantle, and move than conventional rail systems. System extension while in operation may present problems difficult to overcome due to the need to extend the power and control systems as well as the siderail tracks.

The siderail system has the advantage of being the only concept which can transport all types of materials in any attitude; although problems may be encountered with some materials. Another problem is that different power and heat dissipation requirements for vertical lift cars and horizontal operating cars make it difficult and costly to incorporate into one module both sets of requirements.

Monorail - The monorail system is about average in operating cost over all capacity ranges. The equipment cost is two to four times as high as all other systems except the pneumatic pipeline. This excessive equipment cost is due to the high cost of the structural support system assumed. If support can be obtained from the sides or crown of the tunnel this system would become more competitive. The monorail system becomes more competitive in the lower capacity ranges, particularly in the smaller tunnels where it produces one of the lower cost integrated systems.

Because of the overhead support the monorail system could handle larger irregular shapes suspended under trolley unit. Its elevated position in the tunnel would be a disadvantage in serving intermediate loading points. Special design might be required to assure safety with overhead transport.

The overhead support also complicates system installation, removal for reuse, and extension. Material handling in the near-face zone is complicated by the fact that the vehicles must be lowered in elevation for loading and unloading. The incline which can be traversed is limited without resorting to an auxiliary drive such as the rack and pinion.

Conveyor - Conveyor systems offer average to above average operating and equipment costs over the entire range of capacities, except in the very low capacity range where the operating costs drop below average (equipment costs become very high in this range) and at very high capacities where equipment specific costs for standard speed conveyors increase with capacity to become one of the more costly systems.

Claims have been made for transporting limited quantities and shapes of discrete materials on the return flight of a conveyor belt but, since it is unlikely that the total requirement for incoming materials can be met by this mode, there is little incentive for development of this technique.

Conveyors are limited in accommodation of special muck conditions such as hot rock or wet-running or sticky material. Availability under tunneling conditions would probably be less than for more rugged systems; belts and rollers are vulnerable components in the system. Maintenance could be difficult if a belt of several thousand feet length were to break and spill its load at high speed.

System extension would be difficult if it is necessary to splice in a new belt without unloading the conveyor. Three potential methods of extending a belt conveyor system are described in Chapter 3. Only one of the methods (the series of independent units) can be said to be continuous, and that is purely theoretical as it depends on precise timing in the installation sequence. The other methods depend upon a system shutdown to allow time for belt splicing.

Hydraulic - The hydraulic system offers the lowest equipment cost of any transport mode over the entire capacity range. The operating costs, compared to the side-wheel drive, are about 40 percent higher in the low capacity range and about six times as high at very large capacities. The hydraulic concept offers a low cost system for small tunnels and an average system for large, deep tunnels.

The major disadvantages of this concept appear to be the difficulty of system extension, the need for drainage before dismantling for moving and the large size equipment needed for loading material into the system, particularly if crushing is required. It is one of the poorer systems in accommodating variations in material flow rate and would be very difficult to provide for intermediate loading points.

There have been very few attempts to use hydraulic transport systems in tunnels, and these were not too successful. The cause of some of the failures can be attributed to insufficient research and testing preliminary to design which resulted in systems incapable of handling the size, type, and heterogeneous nature of the material to be pumped. On the other hand, where a thorough investigation of the physical properties of the material to be handled has been made, including a comparable scaled operation of prototype equipment, the final installations have been successful. Present installations are fully automated.

Hydraulic transport of material has proved to be the lowest cost method of moving large quantities of bulk material in the mining and dredging industries. Figures of less than $0.10 per cubic yard for dredging and disposal were not uncommon fifty to seventy-five years ago; and surprisingly, in spite of inflation, such low costs are still being achieved. The reasons for sustained low-cost operation are the inherent basic simplicity of a hydraulic system and the minimum operating personnel required. Also, the design of pumps has continually raised the pumping efficiency more than offsetting the increased initial and maintenance costs of the equipment.

Hydraulic systems have several major advantages. They occupy a minimum of the cross-sectional area of a tunnel and are capable of transporting material on any grade from horizontal to vertical without transfer systems. The system is inherently rugged. All machinery and pipe is constructed in a way which is difficult to damage. After the system has been drained, the pipes and pumps are easily uncoupled and transported. The pump and motors can be installed on foundations which facilitate their movement.

Hydraulic systems operate best in continuous operation. Failure of pumps and controls are the main contributor to unavailability and pumps are easily repaired.

Installing the system in the near-face zone would be a rather complex operation. Crushers and mixing tanks must be advanced with the system, and pipe segments must be added without disrupting flow. Although pumps are not difficult to repair, the system must be flushed before a scheduled shutdown for maintenance.

Transporting muck to a suitable disposal site is easily accomplished by pumping; recovery of the water and disposal of the wet muck will require separating and settling equipment.

The use of large quantities of moderate to high pressure water in a tunnel may be questionable from a potential flooding viewpoint, and the system will require automatic shutoff devices, particularly if a continuous system is used for vertical and horizontal transport.

Pneumatic - Projections based on the present state of development of the pneumatic pipeline system indicate that for horizontal transport, it will be by far the most expensive of the systems investigated. Equipment costs are 2 to 4 times as much as most other systems and operating costs, primarily due to the power requirement and maintenance, are 15 to 20 times as much as average systems and over 100 times as much as the side-wheel drive system at very high capacities.

Capacities of developmental pneumatic pipeline systems are in the 300-ton-per-hour range over horizontal distances of approximately 1,000 feet. To be competitive with other modes of transport, this type of system would have to be capable of much higher delivery rates over much longer distances.

The apparent ease of system installation, extension, and relocating are the major attractions of the system. Achieving the cost reductions required to make the system competitive for horizontal transport seems remote. Favorable claims have been made for encapsulation, but the size of facilities required to encapsulate and load from hundreds to thousands of tons of muck per hour seem impractical for a tunnel environment.

Vertical Transport

The systems physically suitable for vertical transport are:

- Siderail
- Hoist
- Hydraulic
- Pneumatic

Equipment and operating specific costs for these systems are compared in Figures 13-7 and 13-8. In the capacity range from 1,000 tons per hour to 5,000 tons per hour for a vertical depth of 1,500 feet, the hydraulic system offers the lowest operating cost and the pneumatic system, the lowest equipment cost. Both the systems (siderail and hoist) capable of handling discrete materials have equipment costs approximately 5 to 6 times the cost of the pneumatic system. The equipment specific cost for the hydraulic system increases with capacity above 1,000 tons per hour and reaches the range of the siderail and hoist (which fall sharply with increased capacity) at about 5,000 tons per hour.

The hydraulic system offers the lowest operating costs over the entire capacity range but is only about 25 percent lower than the hoist above 5,000 tons per hour. The siderail system shows operating cost from 50 percent to 300 percent greater than the other systems and increases sharply as the capacity decreases. The pneumatic system compared to the hydraulic has from 25 percent to 100 percent higher operating cost, being more competitive in the lower capacity range.

Siderail - The rack and pinion method of vertical ascent presently used in the siderail system is limited by the power units to about 4 to 5 miles per hour. The system exhibits the highest operating and equipment costs of any of the concepts investigated for vertical or inclined lifts. This appears to be due primarily to the cost of the guideway and the drive mechanism, the use of relatively small modules and power units, and the lack of a regenerative power system.

Although in its present configuration this is an expensive system, it is the only concept investigated which has demonstrated ability to travel in all attitudes and offers the possibility of handling all types of materials.

Hoist - The hoist system is the most thoroughly tested of all those suitable for vertical or inclined application. It is the historic "workhorse" for lifting and lowering in mining and underground excavation projects. It can be equipped with skips and cages to handle all types of materials in any size up to the limits of the shaft. Its major disadvantages is the inherent cyclic nature of its operation.

Hoist equipment costs are high, becoming the highest of all systems investigated for vertical or inclined lift above 3,000 tons per hour. Operating costs, however, are lower than other systems with vertical capability except for the hydraulic system, which can transport only muck.

The ability of the hoist to accommodate surges in material flow and continuous bidirectional flow is poor due to the reciprocating operation and the fact that the only means of increasing capacity is to increase the speed of travel or to increase the load per lift. The cost of providing shafts will be a major item in deep tunneling. The conventional skip hoist makes rather inefficient use of shaft space. In all other respects the hoist is average or above average in performance. Hoists can be operated on inclined guideways if desired.

Hydraulic - As discussed under horizontal transport, the hydraulic system has been used successfully for limied application in mining operations with particular attention directed to lifting material from the mine. It exhibits the lowest operating cost of any system capable of vertical lift, over the entire capacity range. Since the equipment specific cost increases with capacity above 1,000 tons per hour, the cost advantage of the system decreases as the capacity requirement increases.

For depths up to 3,500 feet, the pressure head exceeds 100 atmospheres unless staged circulating loops are used. The hazard resulting from large quantities of water under these high pressures would need to be carefully evaluated and designs developed to assure safety before application of this concept.

The small cross-sectional area requirement is an important factor when considering shaft size. Eight to ten square feet of cross-sectional area is sufficient to install the return and discharge line of any hydraulic or pneumatic system. Any other vertical lift method requires 100 to 200 square feet of shaft area which equates to one or two additional hoisting shafts (or compartments if one very large shaft is used).

The severe problem of system extension is eliminated if the hydraulic system is used only in the vertical attitude. It can also be used in inclined shafts if desired.

Pneumatic - The pneumatic system exhibits the lowest equipment cost of any lifting system investigated. Its operating costs lie between the hydraulic and hoist systems in the lower range (less than 600 tons per hour), but become increasingly greater than either of these above 600 tons per hour. Due to the rather severe extrapolation from existing data required for cost analysis of this system, more attention should be given to larger scale demonstrations in the vertical attitude. The pneumatic system appears to have attractive prospects, particularly for vertical lift through exploratory bore holes in the lower capacity range and limited tunnel depths.

Due to ease of installation, removal, and reinstallation and the greater assurance of safety, this system may show an overall advantage when compared to the hydraulic system, even though it has a higher operating cost. This system could be used in inclined shafts if desired.

Inclined Transport

The systems physically suitable for inclined transport are:

- Side-Wheel Drive
- Cable Drive
- Siderail
- Hoist
- Conveyor
- Hydraulic
- Pneumatic

Equipment and operating specific costs for these systems are compared in Figures 13-7 and 13-8.

The siderail, hoist, hydraulic, and pneumatic systems are also capable of vertical transport as discussed previously and would, therefore, probably not be used in inclined transport except in cases where shafts were inclined for reasons other than material transport. The side-wheel drive, cable drive, and conveyor are all proven systems for inclined transport but there is room for improvement in the grades which they can effectively traverse.

In the capacity range from 1,000 tons per hour to 5,000 tons per hour the inclined transport systems bracket the operating costs of all (except the costly siderail system) systems with lifting capability. Over the entire capacity range the side-wheel drive system offers the lowest operating cost. The cable drive operating costs, for all practical purposes, are the same as the hoist which is about twice the side-wheel drive cost in the high range and about three times as costly in the low range. Conveyor operating specific costs are rather insensitive to capacity so they vary from 40 percent higher than side-wheel drive in the low range to about 5 times as large in the high range.

Equipment specific cost for the inclined transport systems group within 50 percent at about 5,000 tons per hour where the conveyor and side-wheel drive cost curves cross. As the capacity decreases, the side-wheel drive and cable drive specific costs increase more or less in parallel, while the conveyor cost rises slowly until the side-wheel drive and cable drive costs are about twice the conveyor cost at 400-tons-per-hour capacity.

Side-Wheel Drive - The side-wheel drive and siderail systems are the only ones investigated which have the capability to transport all materials horizontally and also lift and lower them to and from the surface. The side-wheel drive offers operating and equipment costs significantly lower than the present configuration of the siderail system. In fact, the side-wheel drive system operating costs are the lowest of all systems investigated with lift capability over the entire capacity range.

The side-wheel drive system has been demonstrated for use on inclines and offers the possibility of being modified to operate in vertical or near-vertical shafts, although it has not as yet been demonstrated for these severe grades. Since the increased length of inclined shafts of less than 45-degree slope would increase significantly the cost of the access way, investigation to increase the climbing ability of this concept appears warranted.

Perhaps the ideal, all-purpose transport system for tunneling is conceptually somewhere between the side-wheel drive and siderail systems.

Cable Drive - The cable drive system is a very old concept, but it has never been used at the speeds which would be required in the upper capacity range. It offers equipment and operating costs which lie between the conveyor and side-wheel drive over most of the capacity range of interest. Combined with the locomotive drive system for horizontal haulage, it provides an integrated system with overall costs in the same low range as the side-wheel drive system.

As with the side-wheel drive system, the maximum practical slope and speed of operation remain to be determined. The major problem areas are the means of engaging vehicles to the cable drive at the speeds required, the question of safety, problems of reliability and maintenance, and difficulty of installation, dismantling, and moving. Innovative design is needed in all these areas.

Conveyor - The conveyor systems, due to its maintenance history, appears progressively less attractive as a lifting device as the capacity requirement increases. In the lower capacity range (between 200 and 400 tons per hour) it competes favorably with the other methods of lifting. The maximum practical incline of the trough conveyor is well known but would probably need to be improved for economical application to lifting from deep tunnels. Principles of the serpentine concept might find application, or more uniform distribution of the driving force might be obtained by application of the linear motor principle to the conveyor to remove the load concentration from the head pulley as the angle of incline is increased.

RESEARCH AND DEVELOPMENT PROGRAM

A research and development program to advance the state of the art for material handling in tunneling projects should be pursued on a broad front since it is impossible at this point in time to identify with assurance the transport modes which will be most practical and economically advantageous for handling materials which have not been specifically defined, and for which the flow rates and specific environmental conditions are not known.

Problem areas to which research and development resources can be beneficially allocated can be identified in two major groups; those related to the transport modes, and problems or areas of uncertainty related to other aspects of the tunnel project but having cost impact on material transport. For example, problems associated with detailed material handling operations for loading and unloading, intermode transfer, tunnel strategy, and unexpected rock conditions can have a strong impact on the relative merit of the various transport modes.

Conventional Rail Systems

The conventional rail systems (side-wheel drive, locomotive drive and cable drive) offer the most materials haulage capability and flexibility at the lowest total system cost potential of all transport modes investigated, and their competitive position appears to improve as the capacity requirement increases. This makes these systems a prime target for further development to meet the requirements of the future.

Several areas worthy of specific research and development effort for conventional rail systems, most of which would also be of value when related to other unitized systems such as siderail, monorail, hoist, and truck, are:

- A more detailed definition of the interrelationship and limits of transport system design parameters such as cycle time, loading and unloading frequency, loading and unloading time, material scheduling in the near-face zone, vehicle capacity and size, tunnel occupancy factor, length and spacing of trains, maximum and average speeds, structural support requirement, guideway cost, power requirements, and angle of incline over a wide range of tunnel diameters and advance rates.

- Requirements, limitations, and feasibility for various types of roadbeds and structural support methods. Evaluation of the use of muck with a stabilizing agent as a roadbed and the feasibility of using prefabricated track and track support sections.

- Faster methods of loading rail cars and unloading them into transfer mechanisms are needed. This requirement not only is applicable to muck handling but also to the handling of the tunnel support materials in the shaft station and the near-face zone.

- A need exists for the development of techniques and equipment for extending track and roadbed materials at speeds commensurate with the projected tunnel advance rates. Present-day methods do not meet this requirement in a dead-end tracklaying situation.

- Automation for conventional rail systems in the tunneling environment. There are several types of control systems available, but none of them appear to be developed for use in this type of application.

- Develop specialized cars for handling incoming materials.

- Develop near-face zone equipment necessary to load muck, unload materials, and switch cars at the required rates.

Side-Wheel Drive

The side-wheel drive system appears to offer the best potential for a single mode system. Further development of this concept should include the following tasks in addition to those related to conventional rail system in general.

- Determine the maximum length of train that can be pushed, without buckling.

- Determine design effort necessary to adapt for tunnel operations and to increase system capacity to meet requirements.

- Reexamine economics, particularly for small-diameter or low-advance-rate tunnel applications.

- Develop easily installed power stations.

- Examine the potential for transporting men and develop special cars for this purpose.

- Develop capability for the system to operate in a vertical or near-vertical shaft. Investigate feasibility of combining features of the side-wheel drive, cable drive, siderail, or hoist concepts.

Locomotive Drive

The locomotive drive system, which is a rugged, thoroughly-proven concept, offers favorable economics, particularly in the high- and very-high-capacity ranges. Combined with the cable drive or hoist systems it provides low-cost integrated systems which improve in competitive position with increased size. This system should be further developed for use in the event the side-wheel drive system proves to be impractical or uneconomical in certain capacity ranges. The major development effort, other than that associated with the conventional rail systems in general, is related to the lifting mode which could be cable drive, hoist, or some means of applying a distributed propulsive force such as a linear motor or the side-wheel drive.

Cable Drive

Many problems would need to be identified in detail and overcome to make this concept practical in the high-capacity range of interest. The overall feasibility of the concept should be verified by more detailed engineering analysis. Some of these problem areas, in addition to those related to conventional rail systems in general, are:

- Interrelationship of speed and incline, and limiting values of each of these parameters.
- Means of coupling vehicles to the cable.
- Safety, reliability, and maintenance problems.
- Control systems and accelerating systems (hydraulic rams) required to phase the muck cars on the cable system.

Hoist

The principle of the hoist system might be applied for raising and lowering conventional rail vehicles or supplementing other drive systems for this purpose in either vertical or inclined shafts. Problem areas for investigation include:

- Interrelationship of speed and incline, and limiting values of each of these parameters.
- Means of loading and unloading individual vehicles from the hoist in the vertical attitude.

- Means of simultaneously transporting bulk and discrete materials.
- Means of coupling vehicles to the hoist in the inclined attitude.
- Train and/or vehicle switching and scheduling in the shaft station.

Pneumatic

The pneumatic system, which appears to be by far the most costly for horizontal transport provides little incentive for further development for this application. It might, however, find application for vertical lift, particularly if frequently spaced exploratory bore holes are available for muck transport. Very little, if any, investigation or demonstration of long distance, large volume vertical transport by pneumatic pipeline has been made. A rather extensive investigation and demonstration program appears necessary. This would include:

- Studies to more precisely define areas requiring materials development.
- Determination of the effect of muck characteristics on transport capability.
- Flow characteristics, maximum lift height, and cost for transport in large vertical pipes.
- Determination of limiting values of design parameters.
- Demonstration of technique using at least pilot-scale equipment.
- Examination and demonstration of economics of large systems.
- Investigation of possibilities for reduction of power demand.
- Investigations leading to the reduction of maintenance on pipes and other equipment.

Hydraulic

The hydraulic pipeline system offers the lowest equipment cost for horizontal transport and the least operating cost for vertical lift. Although its competitive position appears to decrease with increasing tunnel size, it may be attractive as a means of reducing the demands on other transport modes, particularly for vertical lift in small tunnels.

Included among the evaluation and development efforts which would need to be performed are:

- Examine status of the basic system and determine the design effort necessary to adapt for tunnel operation.
- Determine muck characteristics and the relationship to slurry flow in all attitudes from horizontal to vertical.
- Determine engineering design parameters for slurries produced by typical rock types.
- Assess the problems of industry acceptance, particularly with regard to the question of safety.
- Develop methods and economics for dewatering, fluid recycle, and acceptable disposal of muck.
- Develop optimum methods and economics for crushing muck to the level required for slurry transport.
- Develop method for transfer from horizontal to vertical attitude or other means of reducing pressure on the horizontal loop.
- Develop larger, easily transportable pumps and power stations.
- Develop the near-face equipment necessary to extend the system continuously without interrupted operation.

Siderail

Although high equipment and operating costs are indicated for the siderail system, which appears to be designed for maximum flexibility in haulage of bulk materials, is based on sound principles and becomes more nearly cost competitive as the capacity increases. Several areas directed primarily at cost reduction might be investigated for both horizontal and vertical attitudes of travel.

- Conduct value engineering program on siderail design for specific needs of tunneling project.
- Explore possible means of reducing cost of structural support including possibility of support from tunnel surface or ground support system.

- Investigate less costly power and drive units and higher speed units for climbing.

- Investigate compatibility of horizontal and vertical systems.

- Develop less costly container design.

- Develop crossover switching and system extension methods and equipment.

Monorail

Since the monorail concept approaches a cost competitive position in the smaller tunnels and offers the possibility of freeing the tunnel floor for other uses, investigation directed to reducing structural support cost should be performed since this appears to be the major cost factor contributing to the adverse cost position.

- Analyze and test rock bolts and/or other means of structural support from the tunnel crown or walls.

- Investigate capability for transport on inclines.

- Develop design concepts for vehicles, drive units, loading devices, switching, and system extension.

Conveyor

Conveyor systems appear to be cost competitive in the very low capacity range (200 to 400 tons/hour) and, therefore, are of interest as a possible short-term solution for muck transport. Several problem areas should be investigated.

- Develop method of rapid system extension with minimum interruption of material flow.

- Develop durable belt splice that can be installed in much less time than is presently required.

- Develop means of traversing steeper inclines without sacrificing capacity, possibly using features of the serpentine concept.

- Investigate application of linear motor or side-wheel drive principles to provide distributed propulsive force and remove deadweight load from drive unit in inclined application.

Trucks

Although there appears to be little incentive for increased developmental effort applied to trucks for transport in tunneling operations, their versatility makes them attractive as a possible transporter for other underground excavations where route flexibility is a prime consideration. Areas for worthwhile development are:

- Investigate special uses for trucks such as handling large pieces of equipment or liners.
- Development of longer-life tires or tire protective systems (special chain systems are available) to increase resistance to excessive wear on rough abrasive surfaces. A cost trade-off between this apprach and developing rapidly-installed, smoother surfaces should be made.
- Investigate feasibility of automated truck transport system.
- Develop power boosters to improve grade-climbing capability.

Other Research and Development Needs

Near-Face Zone - The problems associated with the near-face zone comprise an important portion of all material handling problems in tunneling projects. Material handling within the near-face zone has not been treated in detail in this report. Although Part 2 points out the problems associated with unloading the quantities and varieties of incoming materials, implacing liners, extending the material handling system, and other supporting functions. At the high advance rates considered, there appears to be no obvious solution to the complex problems created in this zone. The space limitations, unloading rates, installation rates, and scheduling requirements create the need for systematically designed, special-purpose equipment. A high degree of mechanization is implied by the requirements outlined. The requirements and integration of the special-purpose equipment is too complex to be approached haphazardly; design of this equipment will require additional analysis. A number of manning/automation trade-offs should be examined. A few examples of equipment which probably will be required are:

Liner emplacement machinery
Unloading devices for incoming material
High-speed rock bolt emplacement equipment
High-speed tracklaying equipment

High-speed roadway preparation equipment
Special maintenance and checkout equipment
Control and communications equipment.

Several other problems related to the operational aspects of the near-face zone which should be investigated in detail are:

- Material Flow, Transfer, and Switching

    On-line queues
    Feasibility of intermediate, short-term storage
    Switching problems
    Material packaging

- Automation of Near-Face Zone Operations

Shaft Station - A similar set of problems are apparent in the shaft station area, particularly if multi-mode integrated systems are used. Areas for potentially beneficial investigation are:

- Temporary surge storage. The need for this storage should be weighed against the cost of providing space and equipment.

- Special equipment required if shaft station storage is used.

- Material flow in the shaft station.

- Automation of shaft station operations.

Tunnel Project Strategy - When planning and programming large tunnel complexes, the overall strategy requires that each tunnel or tunnel complex be examined in relationship to the other tunnels and shafts. The major aspects of such a study might be:

Shaft Complex - For a given portion of a tunnel project the number, size, and attitude (inclined or vertical) of shafts comprising a shaft complex are important material handling factors. The quantities and characteristics of muck and construction materials influence the size needed and perhaps the number of access shafts. The cost of sinking different sizes and numbers of shafts must be evaluated against alternate material handling system costs to arrive at a minimum and/or preferred relationship between shaft-complex and material handling.

Shaft Spacing - Since future tunnel projects may involve routes of 400 miles or longer, it is apparent that there must be multiple headings and thus, multiple material handling systems. The spacing of shafts must be selected in order to maximize the effectiveness of the individual material handling systems and the total set of material handling systems, all on a minimum tunnel project cost basis.

Life Cycle Aspects - For the advance rates considered in the study, the driving of a tunnel from one shaft station to the next shaft station can be a matter of just a few months. The setup, dismantle, and movement of portions of the material handling system must be examined in relation to time and cost for the tunnel distance planned to be driven.

Risk Analysis of Material Handling Systems - An important consideration in the selection of a material handling system is its flexibility in handling unexpected rock conditions. An element of risk is involved in implementing a material handling system which can handle the expected rock conditions but may be less effective for other than normal rock conditions. Without 100 percent sampling of the tunnel rock profile, a conservative approach is usually taken in the selection of all equipment, including the material handling system. Study should be directed at the use of optimum material handling systems in good rock and its associated risk. In addition, alternate or contingency plans should be developed and incorporated in the material handling system design for the possibility of bad rock conditions.

APPENDIX 4A

SPECIFICATION OUTLINE FOR MATERIAL TRANSPORT SYSTEMS
(Partial List of Items)

A. MUCK REMOVAL SYSTEM

1. Muck Characteristics

   a. Mass flow rate in tons per hour
   b. Average size of muck blocks
   c. Density of muck after swell factor is applied
   d. Percentage of moisture content
   e. Cohesiveness of muck
   f. Adhesiveness (stickiness) of muck

2. System Operating Requirements

   a. Maximum length of system
   b. Continuous operation during system extension
   c. Percentage of system availability
   d. Life of system in hours or in miles of tunnel

3. System Space Requirements

   a. Tunnel cross-sectional area in square feet
   b. Area and volume requirement in near-face zone for

      (1) Muck-loading equipment
      (2) Incoming material

   c. Provision for moving large equipment

      (1) Along the tunnel
      (2) In the near-face area

   d. Muck surge facilities

      (1) In the tunnel or shaft station
      (2) In the muck loading zone

4. Interface With Excavating Machine

   a. Muck delivery from excavator

      (1) Location
      (2) Type of delivery mechanism

         (a) Transfer equipment

5. Loading Equipment

   a. Capability of loading selected horizontal transport system

      (1) Capacity (tons per hour)
      (2) Space requirements
      (3) Can be advanced behind excavator

   b. Capability of loading shaft transport mechanism

      (1) Vertical shaft
      (2) Inclined shaft

6. System Extension Capability and Mobility

   a. System can be extended at the rate of _______ feet per day
   b. System can be removed from tunnel in _______ man-hours
   c. Initial installation of system can be accomplished in _______ man-hours
   d. System can be reinstalled in a new tunnel in _______ man-hours
   e. Guideway installation can be removed from tunnel in _______ man-hours

7. System Costs

   a. Acquisition cost, complete tunnel system, $_______ per hour
   b. System operating cost, $_______ per hour
   c. Demonstrated material handling cost, $_______ per foot of tunnel for _______ miles of tunnel

8. Shaft Transport Requirements

   a. Depth of shaft in feet
   b. Surface unloading facility
   c. Muck
   d. Other material
   e. Personnel
   f. Interface with transport to muck disposal site
   g. Available shaft configurations

      (1) Vertical

         (a) Square or rectangular (size)
         (b) Circular (size)

(2) Inclined (percent grade)

(a) Square or rectangular (size)
(b) Circular (size)

h. Interface with horizontal tunnel transport system

B. INCOMING MATERIAL HANDLING REQUIREMENTS

1. System should be capable of transporting each of the following sets of incoming material. (Sets will not be transported concurrently.)

Set A

a. Precast liners (dimensions), _______ per hour
b. All materials required to extend material transport system
c. Project support materials

(1) Fabricated items, _______ tons per hour
(2) Bulk materials, _______ cubic yards per hour
(3) Miscellaneous small items, _______ pounds per hour
(4) Shapes up to _______ feet long

d. Project personnel, _______ per hour

Set B

a. Shotcrete, dry mixed, _______ cubic yards per hour
b. All materials required to extend material transport system
c. Project support materials

(1) Fabricated items, _______ tons per hour
(2) Bulk materials, _______ cubic yards per hour
(3) Miscellaneous small items _______ pounds per hour
(4) Shapes up to _______ feet long

d. Project personnel, _______ per hour

2. System should be capable of assisting in transport of muck during peak flow conditions

3. Car Off-Loading Requirements

a. Off-loading rate _______
b. Interface with _______

PART 5:
GLOSSARY

GLOSSARY

Adit - A nearly horizontal passage from the surface by which a mine is entered and unwatered. In the United States an adit is usually called a tunnel though the latter, strictly speaking, passes entirely through a hill and is open at both ends. Frequently also called Drift or Adit level.

Anchor Bolt - A foundation bolt, a drift spike, or other device used for holding any mechanism or structure down. It may or may not be threaded.

Back - That part of an opening which is nearest the surface in relation to any portion of the workings of the mine; the roof.

Back Fill - The rough material used to fill in again a place from which the earth has been removed.

Bottom - The landing at the bottom of the shaft; or, the lowest point of mining operations.

Breasting - Horizontal boards used to retain the face of the tunnel temporarily during mining. The boards usually are held in place by vertical timbers and hydraulic jacks known as "breast jacks."

Bulkhead - An airtight partition of steel or concrete used to retain air pressure within a tunnel. Through this bulkhead pass the man locks and muck locks.

Cable Drive System - A material transport system of the general type employing individual units or trains of load-carrying vehicles pulled by a continuous loop cable and traveling on a conventional dual rail track.

Cage - A frame with one or more platforms used in hoisting men and materials in a vertical shaft.

Chemical Grout - A combination of chemicals that gel into a rubbery substance after they are injected into the ground to solidify water-bearing soils.

Collar - The area in the immediate vicinity of the top of the shaft.

Competent Rock or Ground - Rock which requires very little or no support. That rock which will stand alone without caving or sluffing.

Continuous Systems - Those material transport systems in which the payload material can move in a continuous unbroken stream as in a pipe.

Conventional Rail System - Any material transport system which travels on dual rails of the conventional railroad type. The system may be propelled by any means and be at any elevation related to the ground.

Conveyor System - A mechanism for transporting material on a continuously moving belt which forms a loop from one end to the other of a flight. The system may consist of one or more flights operating in series.

Cost Estimating Relationship (CER) - An equation or factor which relates cost to physical or performance properties.

Cover - The ground between the crown of a tunnel and the surface; in subaqueous tunnels, the distance between the riverbed and the tunnel crown.

Crosscut - A horizontal opening driven across the direction of the main workings. A connection between two drifts, tunnels, or levels.

Crown - The highest part of a circular or horseshoe-shaped tunnel.

Cut-and-Cover - The process of excavating a trench from the surface and then decking it over, usually with timber, so that traffic can be maintained during the construction operation below.

Cutterhead - The front end of a mechanical excavator, usually a wheel, which actually cuts through rock or soft ground.

Drift - A horizontal passage underground. A drift follows the vein, as distinguished from a crosscut, which intersects it, or a level or gallery which may do either.

Drive - To excavate horizontally, or at an inclination as in a drift, tunnel, adit, or entry; distinguished from sinking or raising.

Economy of Scale - The per-unit-output economic benefit normally attained by using larger systems.

Exhaust Fan - A fan used for creating a draft by the formation of a partial vacuum in contra-distinction to a blower.

Face - In any adit, tunnel, or drift, the end at which work is progressing or was last done; or, the surface exposed by excavation (i.e., the working face is the face at the end of the tunnel heading, or at the end of the full-size excavation).

Fan - A revolving machine, to blow air into a mine (pressure fan, blower), or to draw it out (suction fan, exhaust). Modern fans are generally reversible to permit operation as either blower or exhaust.

Figure of Merit - The top level bases used for comparing or evaluating systems or allocating their relative importance; a quantified measure.

Floor - The rock underlying a stratified or nearly horizontal deposit, corresponding to the footwall of more steeply dipping deposits; or that part of any underground opening upon which one walks.

Forepoling - A method of securing adits, drifts, tunnels, or shafts in progress through running ground (i.e., quicksand, etc.) by driving ahead poles, laths, boards, slabs, etc., to prevent the inflow of the running ground on the side and top.

Free Vehicles - Vehicles not limited to a predetermined course by physical constraints but guided over any suitable surface by a driver or automatic control device.

Graveling - The process of forcing pea-gravel into the tail void created by a shield to prevent ground settlement. The process always is followed by cement grouting.

Grout - A thin cement or chemical mixture forced into the crevices of a stratum or strata to prevent ground water from seeping or flowing into an excavation.

Guideway Systems - Those material transport systems using physical constraints to guide the vehicles on a predetermined fixed course.

Haulage - In mining, the drawing or conveying, in cars or otherwise, of the produce of the mine from the place where it is mined to the place where it is to be hoisted, used, or dumped.

Haulageway - The adit, entry, or tunnel through which loaded or empty mine cars are hauled.

Headframe - A structure erected over a shaft to carry the sheaves over which the hoist rope runs for hoisting the cage and skip.

Heading - Tunnel, crosscut, or any underground space in the process of excavation.

Head Room - Height as between the floor and the roof.

Heavy Ground - Very incompetent rock, usually found in faults or shear zones. Highly weathered or decomposed material.

Hoist - An apparatus for raising ore and rock from a mine and for lowering and raising men and material. It consists of a load-carrying vehicle attached to the end of a cable or rope which operates in a reciprocating manner, usually employing a guideway to stabilize the vehicle.

Hoisting Rope - A rope composed of a sufficient number of wires and strands to insure strength and flexibility.

Hydraulic Pipeline System - A pipeline used to transport bulk materials by pumping water through the pipe at a velocity sufficient to propel the material along the pipe.

Idler - A sheave or pulley running loose on a shaft to guide or support a rope.

Incline - A shaft not vertical.

Inclined Tunnel/Inclined Shaft - A tunnel may be driven on an incline up to 30-35 degrees. Generally the distinction between an inclined tunnel versus an inclined shaft is based upon the mode of transport. If transport is by means of self-powered units, such as trucks or locomotives, it is considered an inclined tunnel. An inclined shaft may vary from just off vertical to almost horizontal. As in the case of the inclined tunnel, the mode of transport is the distinguishing feature. If transport is by means of a skip-hoist or cage, it is considered an inclined shaft.

Integrated System - All items including men, equipment, and supplies required to perform a function; in this case, the total material handling function in a tunnel construction project.

Invert - The lowest 90-degree sector of a circular tunnel; the floor of a horseshoe tunnel.

Lagging - Longitudinal wood or steel members that are positioned inside or outside the flanges of ribs. Steel lagging outside the ribs is often used in rock tunnels to prevent falls of small rock. Wood lagging, when used as primary support in soft ground tunnels, also takes the thrust of the shield-propelling jacks.

Level - A horizontal passage or drift into or in a mine.

Linearization - The analytic expression of a value or quantity or the sum of direct-proportion expressions resulting in a simplified expression, usually at the introduction of some degree of error.

Locomotive Drive System - A material transport system of the general type employing trains of load-carrying vehicles pulled or pushed by a prime mover traveling on dual rails beneath the train.

Man Cage - A special cage for lowering and raising men in a mine shaft.

Mode - An operating state or an operating method; in this case, methods or system types for transporting materials.

Model - An analytical expression or group of expressions which describe or relate properties of a system.

Monorail System - A material transport system which travels on a single wide-flange structural steel beam mounted above the load-carrying vehicles which may be propelled individually or as trains by any appropriate type of drive unit.

Muck - Sand, clay, mud, or rock that is excavated from the face and removed from the tunnel.

Near-Face Zone - That area extending from the face back through the muck loading and tunnel support installation area.

Packing - Any material used to fill the void between support members and the rock.

Parameter, Parametric - A well-defined group of analytical terms which together define a measure of physical or performance properties. Parametric analysis defines parameters, their interrelationship, and a range of quantitative values for them.

Pneumatic Pipeline System - A pipeline used to transport bulk materials by blowing or drawing air through the pipe at a velocity sufficient to propel the material along the pipe.

Portal - The entrance to a tunnel that is driven into a hill or mountain.

Post - A mine timber.

Primary Lining - The lining placed as a tunnel is driven to temporarily support the ground until the permanent secondary lining can be placed. In shield-driven tunnels the primary lining may be designed to support the ground permanently without a secondary lining.

Raise - A mine shaft driven from below upward; an opening, like a shaft, made in the back of a level to reach a level above.

Rib - A part of the primary lining, usually made of steel, that is curved to suit the shape of the tunnel section. Also, miners' slang for the walls of a tunnel.

Ribs and Lagging - Elements that make up a primary lining consisting of steel ribs and wood or steel lagging.

Roof or Back - The overhead portion of a tunnel or excavation; i.e., ceiling.

Room - A wide working place in a flat mine; a chamber.

Round - The cycle of drilling, blasting, mucking, and primary lining erection.

Routine - A group (usually large) of equations used in a computer program.

Secondary Lining - A permanent tunnel lining of concrete that is usually placed after mining operations have been completed.

Segments - Sections that make up a ring of primary lining.

Set - The timbers or steel sections which compose any framing, whether used in a shaft, slope, or level.

Shaft - An excavation of limited area compared with its depth, made for finding or mining ore or coal; raising ore, rock, or water; hoisting and lowering men and materials; or ventilating underground workings.

Shaft Station - An enlargement of a level near a shaft from which ore, coal, or rock may be hoisted and supplies unloaded.

Siderail System - A material transport system which travels on wide-flange structural steel beams mounted at the sides of load-carrying vehicles which are propelled by motors and drive units mounted on each individual vehicle. Vehicles travel separately or coupled into trains.

Side-Wheel Drive System - A material transport system of the general type employing trains of load-carrying vehicles propelled by rotating rubber-tire drive units mounted alongside the track and bearing on the vehicles. This system travels on conventional dual-rail tracks beneath the train.

Skip - A container used for raising muck from a tunnel to the surface. Generally the skip travels up the shaft between guides and dumps itself automatically at the surface.

Soft Ground - Heavy ground; rock about underground openings that does not stand well and requires heavy timbering.

Specific Costs - Costs which are ratioed with system capacity and length.

Spile - A temporary lagging driven ahead of last timber set to hold running ground.

Spoil - Debris or waste material from a mine.

Station - An enlargement of a shaft or gallery at any level, thus affording room for landing cages at any desired place.

Subroutine - Part of a larger group of equations used in a computer program.

Subsystems - a functional subgroup of a system, usually performing a well-defined subfunction, e.g., horizontal transport of muck, system extension, loading, etc.

Timber - Any of the wooden props, post bars, collars, lagging, etc., used to support mine workings; one of the steel joists or beams, which have in some mines replaced wooden timbers.

Truck System - A fleet of rubber-tired, self-propelled transport vehicles of either the articulated or rigid frame type which travel unconstrained on a suitable surface.

Tunnel - A tunnel, strictly speaking, is a subterranean passage open at both ends. Often used as a synonym for adit, drift, gallery.

Unitized System - A material transport system consisting of several load-carrying vehicles, or modules. The flowing material stream is divided into discrete units of material.

Wall - The side of a level or drift.

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